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Characterization of NOx emissions from Light-Duty Diesel Vehicles during off-cycle operation

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Characterization of NOx emissions from Light-Duty Diesel Vehicles during off-cycle operation

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Abstract

Characterization of NOx emissions from Light-Duty Diesel Vehicles during off-cycle operation

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Persisting air quality problems in the US have triggered several policy responses that are targeted at lowering the emissions of light-duty vehicles. In addition, the promulgation of Clean Air Act of 1963 and other stringent emissions regulations in the recent times (USEPA Tier 2 Bin 5) to improve the quality of ambient air, mandated the OEMs to develop advanced engine combustion strategies and after-treatment pathways to minimize NOx, PM emissions and attain these ultra-low regulatory targets. Significant difference in emissions rates between certification cycles and real world operation has been observed.

The objective of this study is to conduct in-use emissions testing of light-duty diesel vehicles. Four light duty diesel trucks were tested over four pre-defined, on-road routes, certification and non-certification chassis dynamometer cycles to investigate the difference in emission rates during off-cycle operation. Exhaust emissions were measured using Portable Emissions Measurement System (PEMS).

Results from on-road tests show that NO_x emission rate from one of the four vehicles exhibited 1.2 times higher than the combined average of the other three. All vehicles exhibited NO_x emission rates of 4 – 35 times higher during off-cycle operation compared to FTP-75 standard of 0.04 g/km. CO emissions during the warm engine starts were 48 % lower than tests with cold start. Of all the vehicles, one vehicle exhibited CO_2 emission rate 3% lower than the combined average of the other three. Fuel economy observed on highway routes is 3 % more than other urban and rural routes. On-road emissions rates are 4-35 times higher when compared to emissions from similar cycles on dynamometer, establishing that real world driving emissions are significantly different from those measured on certification cycles.

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1 Introduction and Objectives

1.1 Introduction

Persisting air quality problems in the US have triggered several policy responses that are targeted at lowering the emissions of light-duty vehicles. In addition, the promulgation of Clean Air Act of 1963 and other stringent emissions regulations in the recent times (USEPA Tier 2 Bin 5) to improve the quality of ambient air, mandated the OEMs to develop advanced engine combustion strategies and after-treatment pathways to minimize NOx, PM emissions and attain these ultra-low regulatory targets. Some of the many strategies adopted by the manufacturers include retarding Ignition Timing, Variable Value Timing (VVT), direct fuel injection, Variable Geometry Turbocharger (VGT), Homogeneous Charge Compression Ignition (HCCI), Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR), Lean NO_x Trap (LNT), Diesel Particulate Filter (DPF), and Diesel Oxidation Catalyst (DOC).

In use emissions testing with Portable Emissions Measurement System (PEMS) has become a key element to gauge the correctness/representation of the actual emission values reported from chassis dyno testing, especially in the light duty segment. The on-road emissions tests conducted by independent researchers worldwide, with PEMS show that the real-world NOx emissions of light duty vehicles substantially exceed the regulatory emissions standards. Concerns arise pertaining to the reason that type approval testing under controlled laboratory conditions might not represent the actual on-road emissions of light-duty vehicles with sufficient accuracy. Several studies have indicated that specifically real world NOx emissions of light-duty diesel vehicles during off-cycle operations might substantially exceed the regulatory limit. The present study addresses the knowledge gap in the understanding of off-cycle emissions of light duty diesel vehicles across various topographies, routes and driving cycles. Four light duty diesel trucks were tested over four pre-defined, on-road routes, certification and non-certification chassis dynamometer cycles to investigate the difference in emission rates during off-cycle operation.

1.2 Objective

The global objective of this research is to characterize NO_x emission rates from Light duty trucks during off-cycle operation. The Specific objectives include

1) Conduct in-use emissions testing of four light duty diesel trucks of two different model years using Portable Emissions Measurement System (PEMS).
2) Conduct emissions testing on a chassis dynamometer over certification cycles and real-world cycles developed from PEMS data.

2 Literature Review

2.1 Light Duty Trucks and its Emission regulations

United States Department of Energy classifies Light Duty Trucks into three classes based on their Gross Vehicle Weight Rating (GVWR) as shown in Table 2.1 (U.S. Department of Energy 2012).

Table 2.1 Light Duty Truck Classification based on GVWR (U.S. Department of Energy 2012)

Classes		**GVWR [lbs.]**	**Examples**
Class 1		< 6000	GMC Canyon Dodge Dakota
Class 2	Class 2a	6001 – 8500	Ford F-150, Dodge Ram 1500
	Class 2b	8501 -10000	Ford F-250, Dodge Ram 2500
Class 3		10001-14000	GMC Sierra 3500

Exhaust gas regulations for Light duty vehicles were defined in sets of three (or three tiers) because of Clean Air Act Amendments of 1990. Tier I adopted in 1991 and phased in during 1994 and 1997. While, Tier II standards phased in between 2004 to 2009. Tier II is again sub ranked from Bins 1 to 10, 1 being cleanest and 10 being dirtiest. Tier III standards are sub ranked into seven bins restricting the amount of Non-methane organic gases (NMOG) along with NO_x emissions and is set to phase in from 2017.

These standards are restrictions on emission of Carbon Monoxides, Oxides of Nitrogen, Particulate Matter, Non-methane hydrocarbons. (United States Code 1990)

2.1.1 Phase 1 or Tier I: 1994-1999

In this phase, all new vehicles with gross vehicular weight rating (GVWR) less than 8500 lbs. are categorized into five, one for passenger car and others for light duty truck based on capacity. Emission standards are measured over Federal Test Procedure (FTP-75) and can be found in Table 2.2 all expressed in grams per mile (g/mile). (U.S. EPA 2016)

Table 2.2 Tier I FTP-75 emission standards (U.S. EPA 2016)

Category	50,000 miles/5 years						100,000 miles/10 years					
	THC	NMHC	CO	NOx Diesel	NOx Gasoline	PM	THC	NMHC	CO	NOx Diesel	NOx Gasoline	PM
Passenger car	0.41	0.25	3.4	1.0	0.4	0.08	-	0.31	4.2	1.25	0.6	0.10
LLDT, (LVW <3750lbs)	-	0.25	3.4	1.0	0.4	0.08	0.80	0.31	4.2	1.25	0.6	0.10
LLDT, (LVW >3750lbs)	-	0.32	4.4	-	0.7	0.08	0.80	0.40	5.5	0.97	0.97	0.10
HLDT, (ALVW <5750lbs)	0.32	-	4.4	-	0.7		0.80	0.40	6.4	0.98	0.98	0.10
HLDT, (ALVW >5750lbs)	0.39	-	5.0	-	1.1		0.80	0.56	7.3	1.53	1.53	0.12

2.1.2 NLEV: 1999-2003

National Low Emission Vehicle (NLEV) is a voluntary program that came into effect during the transition period of Tier I to Tier II (i.e. 1999 -2003). During this phase the emissions standards were more stringent and are equivalent to California Low emission Vehicle Program. (U.S. EPA. 1997). These standards are summarized in Table 2.3. Vehicles certified to standards lower than Low emission vehicles (LEV) during this transition phase are known as Transitional low emission vehicle (TLEV) standards. During this phase restriction on alcohols and carbonyls along with Non-methane hydro carbons (NMHC) usually referred as Non-methane organic gasses (NMOG) are phased in, while Tier I restricts Non-methane hydro carbons only. NO_x emission standards for useful life of 100,000 miles/ 10 years is 50% lower than Tier I standards.

Table 2.3 NLEV Emission standards in comparison to Tier I and LEV (U.S. EPA 2016)

Category		**50,000 miles/ 5Years**				**100,000 miles/10 years**			
		NMOG	CO	NOx	PM	NMOG	CO	NOx	PM
Passenger car	Tier I	0.25	3.4	0.4	0.08	0.31	4.2	0.6	-
	TLEV	0.125	3.4	0.4	-	0.156	4.2	0.6	0.08
	LEV	0.075	3.4	0.2	-	0.055	4.2	0.3	0.08
LDT (LVW<3750lbs)	Tier I	0.25	3.4	0.4	0.08	0.31	4.2	0.6	-
	TLEV	0.125	3.4	0.4	-	0.156	4.2	0.6	0.08
	LEV	0.075	3.4	0.2	-	0.055	4.2	0.3	0.08
LDT (LVW>3750lbs)	Tier I	0.32	4.4	0.7	0.08	0.40	5.5	0.97	-
	TLEV	0.16	4.4	0.7	-	0.200	5.5	0.9	0.10
	LEV	0.10	4.4	0.4	-	0.130	5.5	0.5	0.10

2.1.3 Phase 2 or Tier II: 2004-2009

EPA announced update to Tier I emission regulation in 1999, which were phased in from 2004. (U.S EPA 2016). Tier II standards are not based on vehicle weight, instead it was divided into 10 Bins while the 1st is cleanest and the 10th is Dirtiest. Bins from 1-10 apply for light duty trucks and passenger cars. Bins 9, 10 are phased out at the end of 2006, and from 2009 emission standards of light duty trucks must meet with passenger cars. These standards over FTP cycle are summarized in Table 2.4.. During this phase, Sulphur content in diesel was restricted to 15 ppm from 2007 and was made compulsory from 2010. This diesel with 15 ppm of Sulphur is referred as Ultra-Low Sulphur Diesel (ULSD) (U.S. EPA 2000).

During this phase Light-duty vehicle (LDV)/Light-duty trucks (LDT) were required to meet supplemental exhaust emission standards over US06 and SC03 driving cycles in addition to FTP cycle standard and is referred to as Supplemental Federal Test Procedure (SFTP). It also asks manufacturers to calculate their applicable full useful life SFTP standard as follows.

*SFTP Standard = SFTP 1 – [0.358 * (Tier 1 FTP – Tier 2 FTP)]* (40 CFR §86.1811-04).

Table 2.4 Tier II FTP 75 Emission standards

Bins	Intermediate Life (5 years/50,000miles)					Full Life				
	NMOG	CO	NOx	PM	HCHO	NMOG	CO	NOx	PM	HCHO
10	0.125	3.4	0.4	-	0.015	0.156	4.2	0.6	0.08	0.018
9	0.075	3.4	0.2	-	0.015	0.090	4.2	0.3	0.06	0.018
8	0.100	3.4	0.14	-	0.015	0.125	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.090	4.2	0.15	0.01	0.018
6	0.075	3.4	0.08	-	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	-	0.015	0.090	4.2	0.07	0.01	0.018
4	-	-	-	-	-	0.070	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.010	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0.000	0.0	0.00	0.00	0.000

2.1.4 Phase 3A: 2010-2016

This phase is to reduce greenhouse gas emissions by reducing 1.8 billion barrels of oil consumption, and is planned to achieve by the end of 2016 asking an avg. increase of 8 mpg per vehicle. President Barak Obama announced this policy of fuel economy and emission in 2009, to be phasing in from 2010 to 2016. All vehicles under 10,000 lbs. GVWR need to meet average fuel economy of 35.5 mpg based upon Corporate Average Fuel Economy (CAFE) standards (U.S. EPA 2012).

2.1.5 Tier III: 2017-2025

Tier III standards for light duty vehicles were proposed on March 2013, and was signed on third of March 2014. Structure of this standard is similar to Tier II but is closely aligned with California LEV III standards, which also tightens regulation on Sulphur limits in gasoline. (U.S. EPA 2014)

Tier III has seven certification Bins, from which manufacturers have to meet one among those to certify their vehicles. Standards are expressed with the sum of NO_x, NMOG emissions and the average of these emissions must reduce to 30mg per mile by 2025. Durability of vehicles have been increased from 120,000 miles to 150,000 miles. (U.S. EPA 2014)

All vehicles must be certified over HWFET in addition to FTP-75 driving cycle and test procedures. Tier III standards are applicable to all vehicles as shown in Table 2.5.

Table 2.5 Tier III FTP 75 Emission Standards (U.S. EPA 2014)

Bin	NMOG + NOx	PM	CO	HCHO
	mg/mi	mg/mi	g/mi	mg/mi
Bin 160	160	3	4.2	4
Bin 125	125	3	2.1	4
Bin 70	70	3	1.7	4
Bin 50	50	3	1.7	4
Bin 30	30	3	1.0	4
Bin 20	20	3	1.0	4
Bin 0	0	0	0	0

2.2 Light Duty Diesel Emission Control Technologies

NOx and PM emissions from Light Duty Diesel trucks is reduced by 95% and 80% respectively from Tier I to meet Tier II standards. Studies show that these reductions in emissions were achieved through modifications in engine designs through the use of cooled EGR, fuel timing retardation and high-pressure fuel injections (Dickey, Ryan III and Matheaus 1998), SCR is capable of reducing NOx emissions by 90% (Keuper, et al. 2011). Use of NOx traps can reduce NOx emission by 70% or more (Manufacturers of Emission Controls Association 2007). Particulate Matter can be reduced by 90% with the use of DPF, and DOC reduces unburned hydrocarbons.

2.2.1 Exhaust Gas Recirculation

To meet 2004 Federal NOx emission regulations manufacturers developed systems for Exhaust Gas Recirculation. EGR is a method through which a portion of exhaust gas is circulated back into combustion chamber through air inlet manifolds. The two principles alluded to reduce NOx using EGR are (1) EGR acts as heat sink reducing peak combustion temperatures, where heat absorbed by EGR is proportional to EGR flow rate ($\dot{m}$) times specific heat at C_p (const. pressure) and temperature difference between EGR and combustion temperature (ΔT).

(2) Secondly, displacing freshly induced oxygen by inert exhaust gas. NOx is formed as a function of Nitrogen (N_2), Oxygen (O_2), combustion temperature and residence time. (Zheng, Reader and Hawley 2003)

The pressure difference that exists between intake and exhaust manifold does not allow free flow of EGR to intake manifolds. Especially in engines with turbo charger, where the pressure at intake manifold is greater than the exhaust, it is difficult to introduce EGR back into intake manifold. Therefore, manufacturers came up with High Pressure and Low Pressure loops.

2.2.1.1 High Pressure Loop EGR

In turbocharged diesel engines, the exhaust is collected upstream of turbo charger, VGT is adjusted to raise the pressure higher than that of intake manifold creating pressure difference. This Pressure difference drives the exhaust gas into intake manifold and is controlled through EGR valve electronically after being cooled. This approach is referred to as High Pressure Loop (HPL) EGR.

HPL EGR in light-duty diesel trucks showed effective results in reducing NO_x to 0.05g/mile (Yokomura, Kohketsu and Mori 2003). At the same time, it has resulted in increase of fuel consumption associated with PM emissions.

Some researchers used venturi to increase pressure drop between the exhaust and intake manifolds facilitating EGR flow into inlet. Using the venturi reduced pumping losses of flow as venturi increases kinetic energy of the flow (Yokomura, Kohketsu and Mori 2003).

2.2.1.2 Low Pressure Loop EGR

In this scheme, the exhaust collected downstream of after treatment and circulated ahead of turbocharger, thus the turbine can utilize all of the exhaust. As the pressure at the exhaust is low and to promote the flow EGR is introduced back into engine at upstream of turbocharger. The pressure difference is adequate to reduce the NOx levels.

Low Pressure Loop EGR has advantages of low fuel consumption when compared to HPL EGR, reduced amount of cooling required for EGR, better mixing of EGR with fresh air. At the same time, LPL EGR has disadvantages over HPL EGR as the carbonaceous material present in the exhaust stream can erode the blades of compressor at high speeds and there is a chance of CO gas emission when unburned oil vapors exposed to higher temperatures (Agarwal, Singh and Agarwal 2011). Approximately 50% reduction in NO_x emissions with no change in PM levels can be obtained using Low Pressure EGR loop with supplemental cooling (Maiboom, Tauzia and Hetet 2008).

Use of EGR reduces NO_x formation proportional to the ratio of EGR. Test performed by (Uchido, et al. 1993) show 50% NO_x reduction at 20% EGR rate at certain boost pressures and fuel injection. Whereas excessive EGR amounts resulted in unstable combustion, misfire accompanied by white smoke emission (Peng, et al. 2008).

2.2.2 Selective catalytic Reduction

To meet Tier II emission standards, 90% reduction in NOx is required. Lean NOx Traps (LNT), Selective Catalytic Reduction (SCR) are the available technologies to meet the NO_x

standards. While SCR is not effective NO_x at low exhaust temperatures. There are studies in which combination of both LNT and SCR are used to avoid necessity of Diesel Exhaust Fluid (DEF) known as passive SCR. (Wittka, et al. 2015).

SCR injects DEF through dosing system into exhaust flow. DEF is aqueous urea solution (AUS 32) contains about 32.5 percent urea and 67.5 percent deionized water by weight as this mixture produces lowest freezing point (Scott Sluder, et al. 2005). Aqueous Urea decomposes completely into ammonia in three steps, in first step water is evaporated (thermolysis) releasing urea, next step release one molecule of ammonia along with one molecule of isocyanic acid, finally isocyanic acid releases another ammonia molecule and carbon dioxide molecule (Scott Sluder, et al. 2005), final equation which is referred as hydrolysis of urea is listed below.

$$(NH_2)_2CO \rightarrow 2\,NH_3 + CO_2 \qquad \textit{Eq. (1)}$$

This ammonia reacts with Nitrogen oxides to form Nitrogen and water thus reducing oxides of Nitrogen. (Khair, et al. 2004)

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O \qquad \textit{Eq. (2)}$$

In the exhaust where oxygen is abundantly available at lean combustion process, the standard reaction shown below is considered less relevant (Koebel, Elsener and Kleemann 2000).

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \qquad \textit{Eq. (3)}$$

Slow reaction takes place only with NO_2 when NO_x/NO ratio is more than 50% as shown below (Bosch and Janssen 1988).

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \qquad \textit{Eq. (4)}$$

Most desired and fast reaction is known to be obtained when NO and NO_2 are in equal ratios. This reaction is given in the following equation, which is also known, as “Fast SCR” reaction (Bosch and Janssen 1988).

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \qquad \textit{Eq. (5)}$$

Ammonia sometimes reacts with Nitrogen dioxide to form ammonium nitrate (NH_4NO_3), which occurs at temperatures below 200º C (Koebel, Madia and Elsener 2002).

$$2NH_3 + 2NO_2 \rightarrow NH_4NO_3 + N_2 + H_2O \qquad \textit{Eq. (6)}$$

Sulphur present in fuel can be oxidized during combustion and over DOC might react with water to form Sulfuric acid which might deactivate SCR catalysts forming Ammonium Sulphate (Huang, et al. 2003) and these reactions are shown below.

$$SO_2 + {}^1\!/_2\, O_2 \rightarrow SO_3 \qquad \textit{Eq. (7)}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \qquad \textit{Eq. (8)}$$

$$2\ NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 \qquad \textit{Eq. (9)}$$

The purpose of SCR is to reduce NO_x and its efficiency depends on many factors such as NO/ NO_2 ratio entering SCR, catalyst material, urea decomposition, and reaction temperatures inside SCR (Keuper, et al. 2011). These parameters are interdependent with each other for SCR performance.

Using SCR with AUS 32 technology 90% reduction in NO_x levels from exhaust gas can be achieved (Keuper, et al. 2011). The same paper also shows that there is chance of increasing conversion efficiency by another 5%, which might drop the necessity of having an EGR.

2.2.3 Lean NOx Trap

Lean NO_x Trap (LNT) catalysts are used to reduce NO_x from lean burn engine. Its works on the principle of trapping NO_x during engine lean operation and reducing the stored NO_x to N_2 under rich conditions with reducing agents like CO, H_2 and THC (Kim, et al. 2003). This process of reducing the NO_x is called regeneration which uses fuel addition (Parks, et al. 2008). Rich conditions can be obtained by injecting additional fuel into the cylinders, reducing oxygen availability and this kind of regeneration is call in-cylinder regeneration. In-cylinder regeneration affects total hydro carbons but did not affect any engine out CO and H_2 emissions (West, et al. 2004).

LNT working temperature window is in the range of 200°C to 450°C, the conversion efficiencies are in range of 80-90% observed at 350-380 °C (Epling, et al. 2004). LNT efficiency drops as the exhaust temperature increases at high engine loads. Can be used only at low loads where SCR is ineffective, and cannot meet Tier II emission standards. Sulphur poisoning of fresh and aged traps requires Desulfation by exposing it to rich feed gas at higher temperatures, NO_x storage efficiency reduces if Desulfation is not performed at regular intervals (Li, et al. 2001).

2.2.4 Diesel Particulate Filter

Diesel Particulate Filter (DPF) is used from 2004 to meet stringent EPA regulations on Particulate Matter. This filter collects particles (ash and soot) which is produced from diesel combustion. The particles accumulate in the filter over time and requires periodic regeneration of DPF. If the soot accumulated is not cleaned, there would be a pressure increase in the exhaust affecting engine operation. Soot is burned at regular exhaust temperatures by lowering oxidation temperatures with the use of oxidation catalyst or NO_x catalyst which is known as passive regeneration and at temperatures from 550 °C to 700 °C by addition of fuel to exhaust gasses known as active regeneration (Kong, et al. 2005). The particle number during a regeneration event is 3-4 times the order of magnitude when compared to particles during normal operational conditions. (Bergmann, et al. 2009), however the efficiency of DPF reduces as the soot-cake layer burns during regeneration (Bergmann, et al. 2009).

“The types of filters used in DPF are divided into three categories as follows:

(i) Non-catalytic filter based systems which use burners and electric heaters to bum the soot once it has been collected on the filter

(ii) Catalytic filter-based systems which consist of filters with a catalyst coating, or filters used in combination with oxidation catalyst ahead of filter to help reducing the oxidation temperatures for passive regenerations.

Tests performed by (Barone, Storey and Domingo 2010) show 95% reduction in particle emission by mass with a 4-year field aged DPF. They also show that particulate filters can capture harmful soot from a range of 30% to 95%. Another journal article by (Herner, et al. 2009) also shows that DPF can reduce >95% of PM irrespective of test cycles.

2.2.5 Diesel Oxidation Catalyst

Diesel Oxidation catalyst was introduced to oxidize harmful gases and diesel particles from exhaust gas. Gases like Hydrocarbons, carbon monoxide have very harmful effects like smog to the environment, which in turn results in adverse health effects. So, these harmful gases are oxidized to harmless by passing over oxidation catalysts.

Catalyst like palladium, platinum and aluminum oxide are used as DOC in after treatment of exhaust gas (Russell and Epling 2011). They serve as oxidation catalysts to oxidize hydrocarbons and carbon monoxides to water and carbon dioxides (Salomons, et al. 2006)

$$2CO + O_2 \rightarrow 2CO_2 \qquad \textit{Eq. (10)}$$

$$C_iH_{2i+2} + \left(\frac{3i+1}{2}\right) O_2 \rightarrow i\, CO_2 + (i+1)H_2O \qquad \textit{Eq. (11)}$$

Along with the oxidation of hydrocarbons, some of the undesired reactions like oxidation of sulfur dioxide to trioxide, which might later react with moisture to form sulfuric acid as follows

$$2SO_2 + O_2 = 2SO_3 \qquad \textit{Eq. (12)}$$

$$SO_3 + H_2O = H_2SO_4 \qquad \textit{Eq. (13)}$$

In addition, oxidation of NO to NO_2 which is more toxic, but can be used for passive DPF regeneration (Cooper, Jung and Thoss 1990) and to control SCR efficiency.

2.3 OBD Monitoring

On-Board Diagnostics (OBD) is a self-diagnostic algorithm in automotive vehicles that monitors the health of various components. Earlier, if a malfunction is detected, OBD illuminates a light called “Malfunction Indicator Light” (MIL) which is not standardized. Later on devices developed standardized communications along with standardized trouble shooting codes, which can be used to identify type of malfunction occurred.

California Air Resources Board introduced OBD I regulation for all 1991 and newer vehicles using light-duty and heavy-duty engines in United States, which requires manufacturer to monitor components that control emissions. Later in 1996, OBD II regulation is implemented which requires all new gasoline and alternate fuel cars and trucks sold in California. From 1997, even diesel cars and trucks are required to follow OBD II regulations. (Santini 2011)

2.3.1 OBD I

OBD I is mostly about engine management, which includes Fuel, Ignition and Cooling. Figure 1 shows how engine management is done by the control unit taking inputs from sensors like to start an engine, inputs from Engine Coolant Temperature (ECT). Vehicle processor uses information from Intake Air Temperature (IAT), Crank shaft Position (CKP) and Cam Shaft Position (CMP) sensors and controls amount of fuel addition, time of ignition as an output. After the start of the engine it monitors other operations like advancing/retarding the timing of ignition through electronic ignition module, turning cooling fan ON/OFF based on engine operating temperature to maintain coolant temperatures. Oxygen Sensor (O_2S) that is present in exhaust manifold is used to control the fuel injection and it is important to check all the injected fuel is burnt. OBD I failed in identifying open fuel injector or a dead cylinder. OBD I dependency on sensors that are inaccurate lead to development of OBD II. (Santini 2011). OBD I codes from early 1980's through 1995 have two and three digit numbers without any letters.

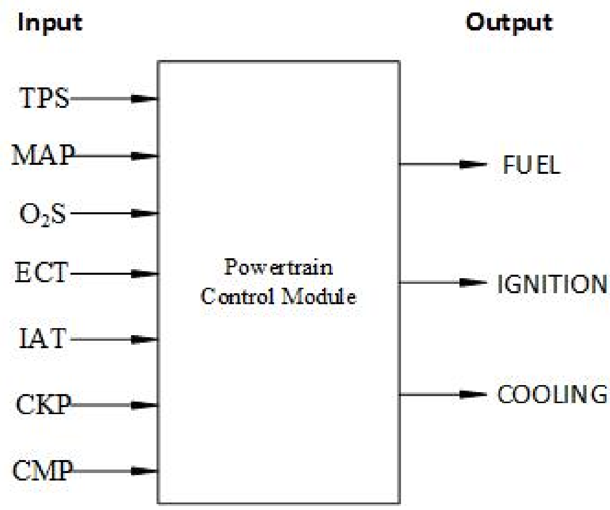

Figure 1 Schematic of OBD I

2.3.2 OBD II

OBD II is an improved version of OBD I in terms of capabilities and standards built inside Powertrain Control Module (PCM) of the vehicle. OBD II is designed in such a way that even a failure in chemical, mechanical and electrical component that might result in failure of emission reduction is considered as a malfunction. If a malfunction in any component is occurred, a freeze frame is generated with all information like speed, load, fuel levels etc. accompanied by MIL and Diagnostic Trouble Codes (DTC). Freeze frame, MIL, DTC are all functions of monitoring system. If OBD monitor cannot finish within the required timeframe it will set a code, OBD erases the code if same malfunction is not detected during next driving cycle (Santini 2011).

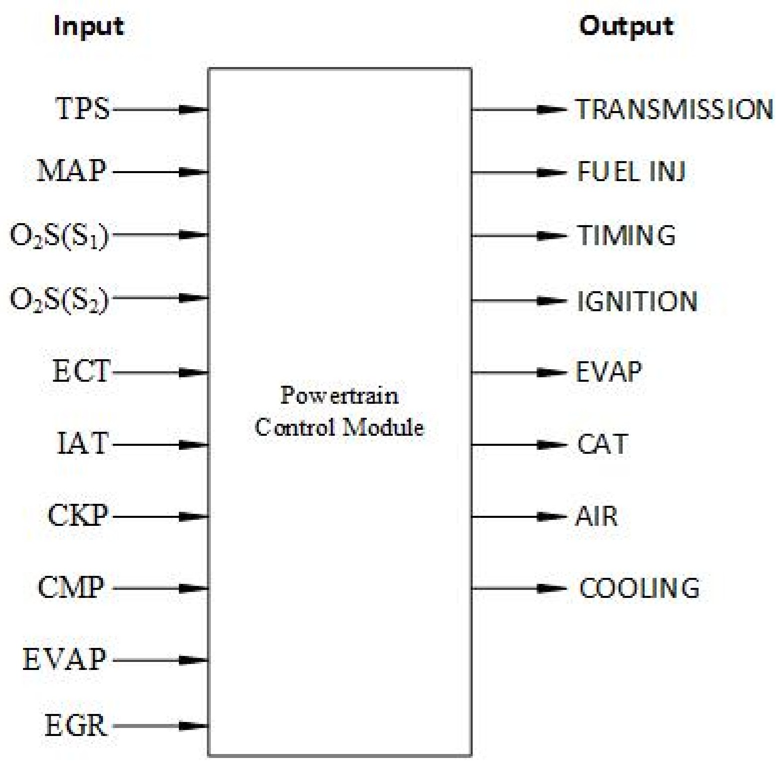

Figure 2 Schematic of OBD II

Various operations that OBD II perform include monitoring all commands given by PCM like Transmission, Fuel injection, valve timing, Ignition timing, catalyst operation, cooling etc. with the feedback from sensors like Throttle Position Sensor (TPS), Manifold Absolute Pressure (MAP), EGR, ECT, IAT, CKP Etc..

2.4 Comparison of NO_x emission rates from chassis and real world

Number of studies have been conducted across US and Europe to compare emission rates from on-road measurements and chassis dynamometer measurements. All those studies show drastic difference in NO_x emissions rates. Summary from some of those studies are discussed here.

Luc Pelkmans and Patrick Debal in 2006 conducted a series of on-road tests and chassis dynamometer tests on a light duty diesel car certified on EURO 3. Dynamometer driving cycles used for this test were mostly focused on was European Drive Cycle (EDC) and cycles that are generated from real world speed profiles as similar to our current study. Whereas on-road testing was done on routes of Belgium and Spain which contain urban, rural and motor way traffic. The reported NO_x emissions rates are 10 times higher on road than compared to NEDC, whereas fuel consumption and CO_2 emissions are underestimated by 10-20 % in NEDC cycle compared to real time traffic (Pelkmans and Debal 2006).

(Anderson, et al. 2014) Performed on-road testing on two Euro 6 diesel vehicles using PEMS and compared the emissions with those obtained on chassis dynamometer. NO_x emissions from on-road routes were ~4 time's higher than those obtained on NEDC cycle. Vehicle with dual EGR showed NO_x average of about 0.17 g/km on-road, while it was 0.02 g/km on NEDC. Vehicle with SCR showed NO_x average of about 0.16 g/km on-road and 0.28 g/km on NEDC cycle. It shows that NO_x emissions are approximately 8 times lower on chassis dynamometer cycles than on-road.

(Alves, et al. 2015) Conducted a series of test on five light duty diesel vehicles and three light duty gasoline vehicles. This study was performed on chassis dynamometer with EDC and ARTEMIS (real-world driving) cycles. The study shows a variation of 5 – 10 times in NO_x emissions levels compared to the standard certification cycles, while some of them could not meet the emission standards. Total hydrocarbon emissions & particles emitted from gasoline vehicles are low when compared to diesel vehicles but emitted particles are negligible for diesel vehicles equipped with DPF (Alves, et al. 2015). The study also shows 35% increase in fuel consumption during DPF regeneration event, while hydrocarbons, NO_x, CO and CO_2 emissions increased by 95, 95, 35 and 99% respectively.

2.5 Chassis Dynamometer Cycles

2.5.1 FTP 72 or LA-4

This is a transient test cycle, which simulates urban route with stops regularly performed on chassis dynamometer for cars and light duty trucks. This test cycle can also be called as Urban Dynamometer Schedule (UDDS) or LA-4.

This cycle has a maximum speed of 91.2 km/h, average of about 31.5 km/h over an urban route of 12.07 km. The following figure is plot of speed vs time of this test cycle.

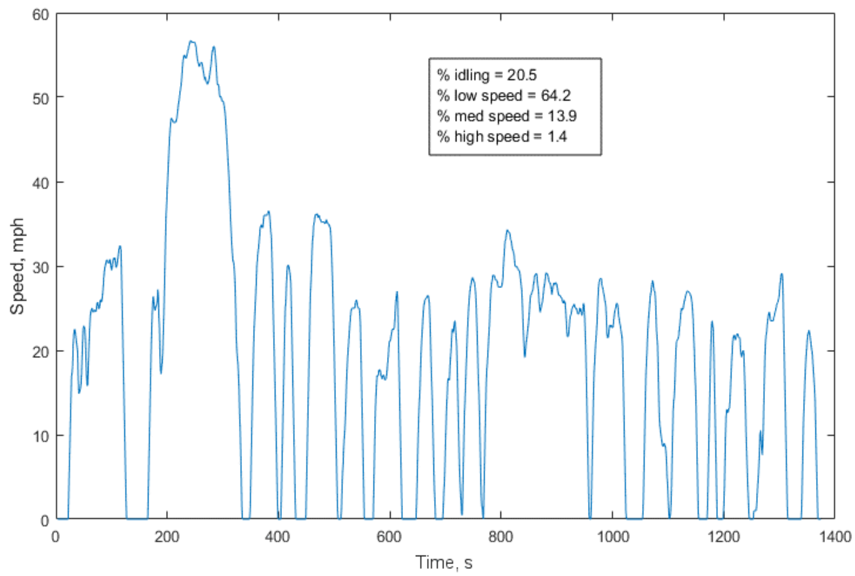

Figure 3 US EPA Urban Dynamometer Driving Schedule (FTP-72)

FTP-72 has two phases; one is a cold start with an average speed of 41.2 km/h for 505 seconds (5.78 km) and other at 25.75 km/h for 867 seconds (6.20 km). Weighting factors for both the phases are 0.43 and 0.57 respectively.

2.5.2 FTP 75

FTP-75 is another variant of Urban Dynamometer Driving Schedule (UDDS). This cycle is used in United States to certify emission and fuel economy testing. FTP-75 has three phases: first two identical to FTP-72, third phase is a hot start for 505 seconds with an average speed of

41.2 km/h for 505 seconds (5.79km) with a soak period of ten minutes after phase two. The weighting factors for each phase is 0.43, 1&0.57 respectively.

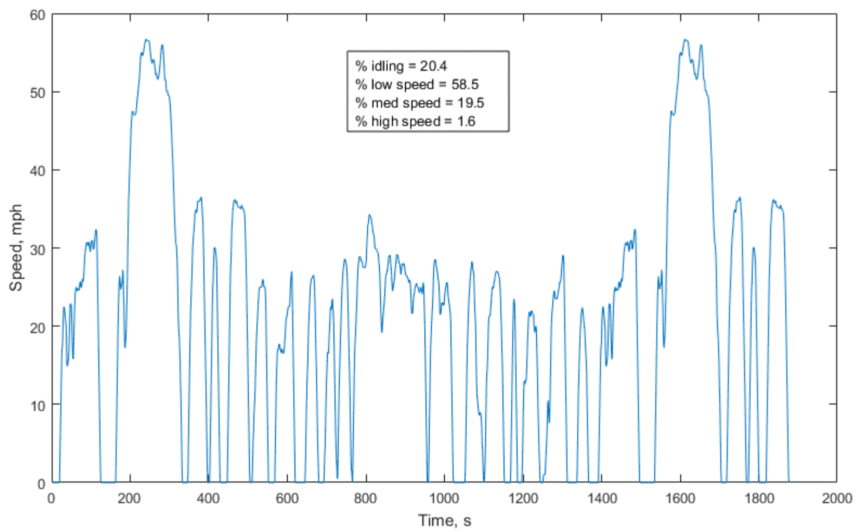

Figure 4 US EPA Urban Dynamometer Driving Schedule (FTP-75)

Total distance travelled in this driving cycle is 17.77 km with maximum speed of 91.25 km/h. Fuel economy calculations are based on FTP-75 HWFET, US06 and SC03. FTP 75 does not have rapid fluctuations or aggressive driving patterns like US06 and LA-4.

2.5.3 Highway Fuel Economy Test

Highway Fuel Economy Test – HWFET is a driving schedule developed to determine fuel economy of light duty vehicles by US EPA. The test run first for pre-conditioning and second time to measure emissions. This driving cycle is for a total duration of 765 seconds covering a distance of 16.45 km with a maximum speed of 96.3 km/h and average speed of 77.7 km/h.

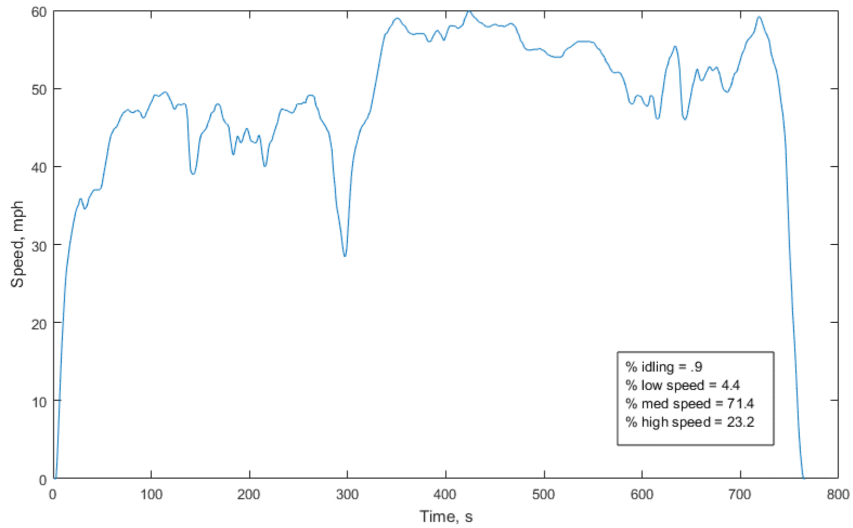

Figure 5 HWFET Driving Schedule

2.5.4 SFTP US06

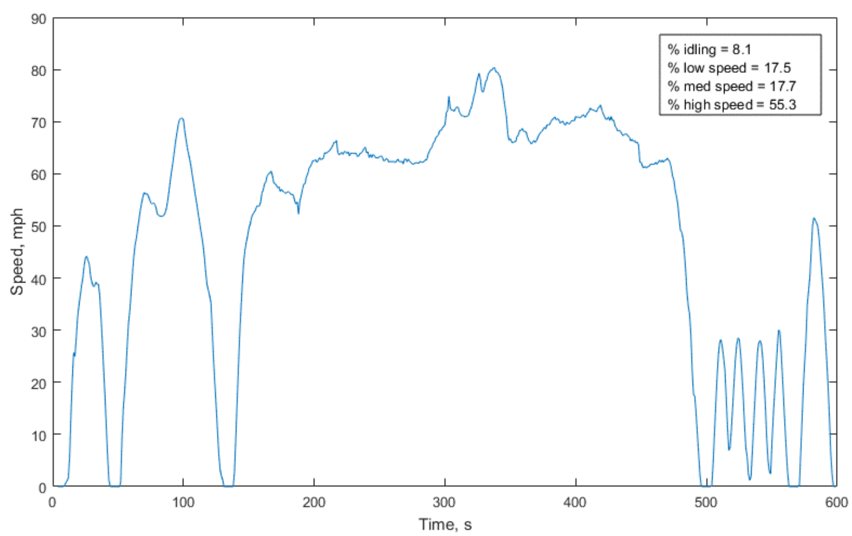

Figure 6 SFTP US06 Driving Cycle

SFTP refers to Supplemental Federal Test Procedure, designed to capture off-cycle emissions that are not reflected in FTP. US06 and SC03 are two cycles that come under SFTP and are used along with FTP-75 and HWFET from Tier II regulations.

US06 is a representation of high speed and quick acceleration cycle, which is over a stretch of 12.8 km with a maximum speed of 129.2 km/h and an average speed of 77.9 km/h for a duration of 596 seconds.

2.5.5 New European Driving Cycle

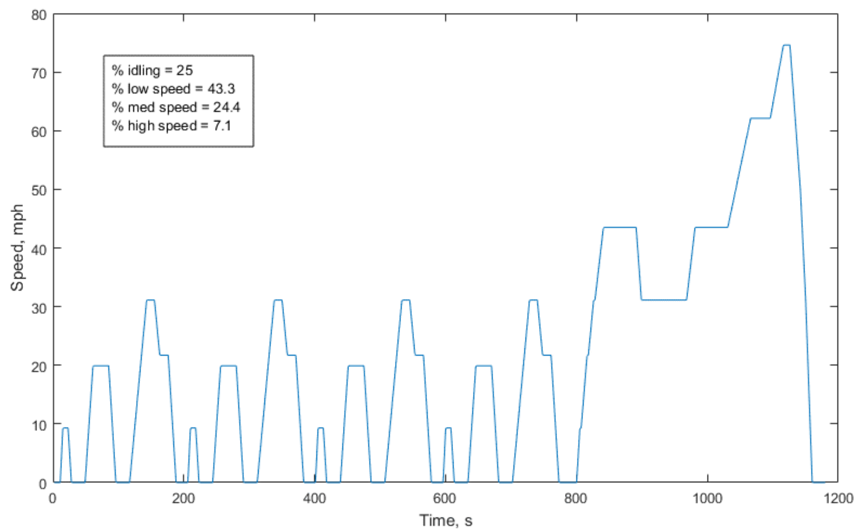

Figure 7 NEDC Driving Cycle

Figure 7 represents New European Driving cycle used to measure emission levels and fuel economy of passenger cars in Europe. This Cycle represents typical road driving patterns of Europe and consists four repetitions ECE-15 also known as urban driving cycle and one Extra-Urban driving cycle. NEDC cycle is over a stretch of 10.931 km with maximum speed of 120 km/h and an average speed of 33.35 km/h including stops and 43.10 km/h excluding stops, total duration of the cycle is 1180 seconds with idle time for 267 seconds.

2.5.6 Morgantown on-road Cycle.

A standard road cycle is developed to represent real-world driving characteristics. Here Morgantown chassis cycle is created with the speed traces measured from real driving in the Morgantown city. This cycle covers a distance of 35.9 km over a duration of 2410 seconds with maximum speed of about 124.7 km/h and an average speed of 53.6 km/h. This cycle represents on-road test route 1 of the current report. Figure 8 represents speed distribution of Morgantown chassis cycle.

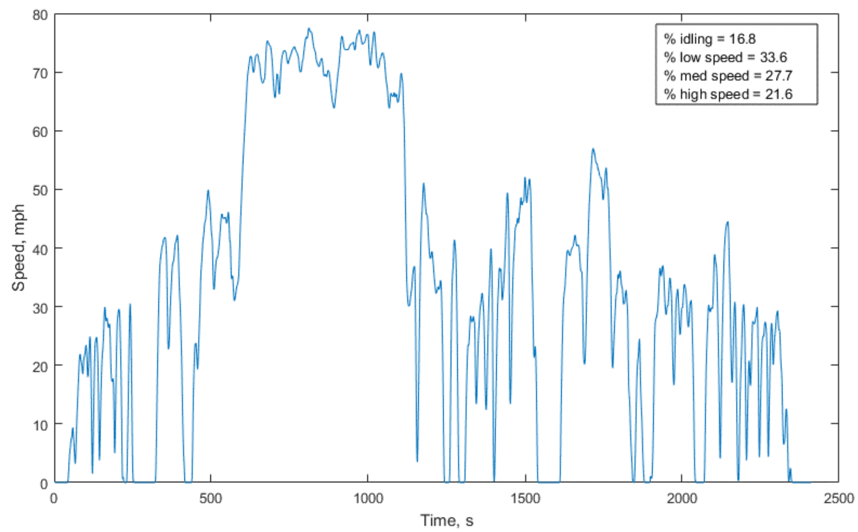

Figure 8: Morgantown Chassis Cycle

2.6 European RDE

European Union's emissions type approval procedures includes Real-Driving Emissions (RDE) test for passenger cars, from September 2017. Ultimate goal of this regulation is to address the high NO_x emissions from diesel cars in real world driving (ICCT 2015).

First European RDE testing requirements are published in March 2016, which states that test routes must contain three segments namely urban (<60 km/h), rural (60-90 km/h) and motor way (>90 km/h) with each segment covering a distance of 16 km at least and contributing for a third of total. This RDE states that CO, NOx emissions should be measured on all Euro 6 vehicles that include passenger cars and light commercial vehicles. It also states that data obtained from

PEMS should be processed in CO_2 moving average window method and power binning method. (European Union 2016).

European Commission – Press release states that RDE testing requirements are introduced in three phases:

1. Monitoring phase – entered into force for new approvals from April 2016 without any Conformity Factor (CF).
2. Approval testing - NO_x CF of 2.1 for MY 2017 to MY 2019 and 1.5 for MY 2020 and later. In addition, Particulate Number (PN) CF to be introduced in 2017 as RDE package 3.
3. In-service conformity requirements are expected by the end of 2016. (Brussels 2015)

RDE emission regulations limits are calculated as a Conformity Factor (CF) with respective NEDC emission limit.

2.7 CAFE Standards

Corporate Average Fuel Economy (CAFE) standards were first established in 1975 to reduce energy consumption by increasing fuel economy of vehicles. Department of Transportation established first fuel economy standards to Light Duty trucks. For MY 2007 engines the economy standards was set to 22.2 miles per gallon (mpg). The energy legislation signed and passed by the then president George W. Bush in 2007 set a goal for economy standard of 35 mpg by 2020. (THE WHITE HOUSE 2009).

Department of Energy (DOT) and Environmental Protection Agency (EPA) worked together to set a new standard of 35.5 mpg by the end of 2020 which surpassed the standard set by CAFE earlier (THE WHITE HOUSE 2009).

EPA and DOT’s National Highway Traffic Safety Administration (NHTSA) set new standards to reduce Greenhouse Gas (GHG) emissions and improve fuel economy. EPA set GHG emission standards under Clean Air Act, which apply to passenger cars, light duty trucks and medium duty passenger vehicles. This standard is set to reduce CO_2 to 163 g/mile by the end of 2025 and fuel economy to 54.5 mpg for MY 2017 through MY 2025 light duty trucks (U.S. EPA 2012). This standard is set to save 4 billion barrels of crude oil approximately and GHG emissions by 2 billion metric tons (US EPA 2012).

3 Test setup and Methodology

Test vehicles selected for this study with their specifications along with the test routes and their details are discussed briefly in Sections 3.1 and 3.2. The sampling instrument and its setup during the test is discussed in Section 3.3

3.1 Test Vehicle information

The Vehicles used for this study comprise one 2015 MY and three 2014 MY engine ultra-low Sulphur diesel (ULSD) fueled Light duty trucks. These vehicles will be referred to as *'Vehicle A', 'Vehicle B', 'Vehicle C' and 'Vehicle D',* and their specifications are shown in Table 3.1. All four vehicles are equipped with 3.0L turbocharged; six-cylinder base engine equipped with urea based SCR system, DOC and DPF to control NO_x and PM emissions respectively. All four vehicles fall into Tier II- Bin 5 of US EPA emission standards whereas LEV-II ULEV in California emission standards.

Gross vehicle weight ratings (GVWR), and Actual test weights, which is a sum of curb weight and payload during on-road PEMS testing is listed in Table 3.2. Payload includes weight of measuring device and its associated equipment, weight of driver and one passenger. The diesel fuel used during this study is ultra-low Sulphur diesel purchased from Sheetz gas station Morgantown.

3.2 Vehicle test routes and dynamometer test cycles

On-road PEMS testing was done over four pre-defined routes, in which first two start and end at Engine and Emissions Research Laboratory (EERL) located at 360 Evansdale Drive Morgantown, while the other two start and end at Vehicle Engine Testing Laboratory (VETL) located at 165 Distributor's Drive Morgantown. These on-road routes are be described briefly in the section 3.2.1. While Section 3.2.2 will describe briefly the chassis dynamometer cycles used during this study.

Table 3.1 Test Vehicles and engine specifications

Vehicle		**A**	**B**	**C**	**D**
Model Year		2015	2014	2014	2014
Engine Family		FCRXT03.05PV	ECRXT03.05PV	ECRXT03.05PV	ECRXT03.05PV
Odometer [km]		3060	21626	28924	43236
Fuel		ULSD	ULSD	ULSD	ULSD
Engine Displacement [L]		3.0	3.0	3.0	3.0
Engine aspiration		Turbocharged/ Intercooled	Turbocharged/ Intercooled	Turbocharged/ Intercooled	Turbocharged/ Intercooled
After-treatment		OC, DPF, urea-SCR	OC, DPF, urea-SCR	OC, DPF, urea-SCR	OC, DPF, urea-SCR
Applicable Limit	U.S EPA	Tier-II Bin 5 (LDT4)	Tier-II Bin 5 (LDT4)	Tier-II Bin 5 (LDT4)	Tier-II Bin 5 (LDT4)
	CARB	LEV-II ULEV	LEV-II ULEV	LEV-II ULEV	LEV-II ULEV
EPA Fuel Economy Values[mpg]	City	19	19	19	19
	Highway	27	27	27	27
	Combined	22	22	22	22
EPA CO_2 Values [g/mile]		459	459	459	459

Table 3.2: Test weights for vehicles

Vehicle	Curb Weight [lbs.]	GVWR [lbs.]	ETW [lbs.]	Payload [lbs.]	Actual Test Weight [lbs.]
Vehicle A	5792	6950	6000	800	6592
Vehicle B	5792	6950	6000	800	6592
Vehicle C	5792	6950	6000	800	6592
Vehicle D	5792	6950	6000	800	6592

3.2.1 Pre-defined On-road Test Routes

Four test routes are prepared such that they start and end in Morgantown, with different topological conditions. Based on the vehicle operational speed these routes can be split into four categories such as i) urban driving, low speeds and frequent stops, ii) rural driving, medium speeds with occasional stops, iii) highway driving, high speeds with few or no stops and iv) uphill/downhill driving, medium to high speed on steeper road grades. (G. J. Thompson, et al. 2014). On-road test route characteristics are summarized in Table 3.3.

1) Route 1: rural and highway driving starting from EERL, Morgantown
2) Route 2: highway and uphill/downhill driving from EERL, Morgantown
3) Route 3: urban, rural and highway driving starting from VETL, Morgantown
4) Route 4: highway and uphill/downhill driving from VETL, Morgantown

Table 3.3: Comparison of test routes

Routes	**Route 1**	**Route 2**	**Route 3**	**Route 4**
Route distance [km]	35.9	102	40	80
Avg. vehicle speed [km/h]	46	93	53	82
Max. vehicle speed [km/h]	120	123	122	125
Avg. RPA [m/s^2]	0.31	0.37	0.34	0.26
Characteristic Power [m^2/s^3]				
Min. elevation [m a.s.l]	260	260	261	275
Max. elevation [m a.s.l]	381	683	385	683
% Idling (≤ 2km/h)	20	5	11	3
% low speed (>2, ≤50 km/h)	41	15	42	15
% med speed (>50, ≤90 km/h)	19	9	27	24
% high speed (>90 km/h)	20	70	20	55

Relative Positive Acceleration (RPA) is a metric used to analyze driving pattern and is used to develop chassis dynamometer cycle representing real world driving. The RPA is calculated as integral of the products of vehicle speed and positive acceleration for each instance in time over a given '*micro-trip*' (Weiss, et al. 2011). For this study '*micro-trip*' is defined as proposed by (Weiss, et al.) for any proportion for the test route, where vehicle speed is larger than 2 km/h for next seconds or more. Instantaneous vehicle acceleration was calculated using the following equation using vehicle speed data which is obtained from OBD-II and subsequently filtered with negative values being converted to zero.

$$RPA = \frac{\int_0^{t_j}(v_i.a_i)dt}{x_j} \qquad \textit{Eq. (14)}$$

Where: t_j duration of micro-trip j

x_j distance of micro-trip j

v_j speed during each time increment *i*

a_j instantaneous positive acceleration during each time increment *i* contained in the micro-trip *j*

Acceleration are calculated with forward difference for first data point, backward difference for last data point whereas central difference for rest of the data as suggested by (G. J. Thompson, et al. 2014).

Characteristic Power (P_{ch}) is another metric derived by (Delgado, Clark and Thompson 2011) taking kinematic power and potential power over the driving route into account. It is a representative of positive mechanical energy supplied per unit mass and unit time. The following equation shows outline of characteristic power calculation in [m^2/s^3].

$$P_{ch} = \frac{1}{T}\sum_{i=2}^{N}\left[\frac{1}{2}(v_i^2 - v_{i-1}^2) + g(h_i - h_{i-1})\right]^+ \qquad \textit{Eq. (15)}$$

Where: T duration of route

g gravitational acceleration

v_i vehicle speed at each time step

h_i altitude at each time step

Gravitational acceleration is taken as 9.81 m/s^2, vehicle speed and altitude at each time step is obtained from Engine Control Unit (ECU) and Global Positioning Sensor (GPS) respectively. GPS sensor data may not be accurate due to multiple factors like heavy cloud overcast, underpasses as well as high buildings, so an alternate method to calculate altitude was used. The following equation as a function of barometric pressure with reference to local ambient pressure and temperature.

$$H = f(T_0, p_0, p_{baro}) = \left(\frac{T_0}{L}\right)\left[1 - \left(\frac{p_{baro}}{p_0}\right)^{\left[\frac{R.L}{g.M_{air}}\right]}\right] \qquad Eq.\ (16)$$

Here reference temperature 'T_0' and pressure 'P_0' at ground level is obtained from local station i.e. Morgantown municipal airport, where as 'P_{baro}' is measured with humidity sensor, 'g', 'R', 'M_{air}' is gravitational acceleration, universal gas constant and molar mass of dry air and 'L' is temperature lapse rate 0.0065K/m.

Table 3.3 represents driving characteristics of test routes on a working day with regular traffic. To compare these results from the road test, vehicles are tested on chassis dynamometer over certification test cycles currently being used by US EPA (FTP-75, US06, and HWFET), the European Union (NEDC) along with two custom made real world driving cycles (MGW and LA-4). Table 3.4 shows comparison of dynamometer test cycles.

The geographic map of route 1 can be seen in Figure 9 and is approximately 36 kilometers in distance, which starts and ends 360 Evansdale drive. This route comprises highway driving for approximately 20% between exit 155 on I-79 South and exit 4 on I-68 East. Altitude elevation difference of 120 meters between highest and lowest elevation points above sea level in the route.

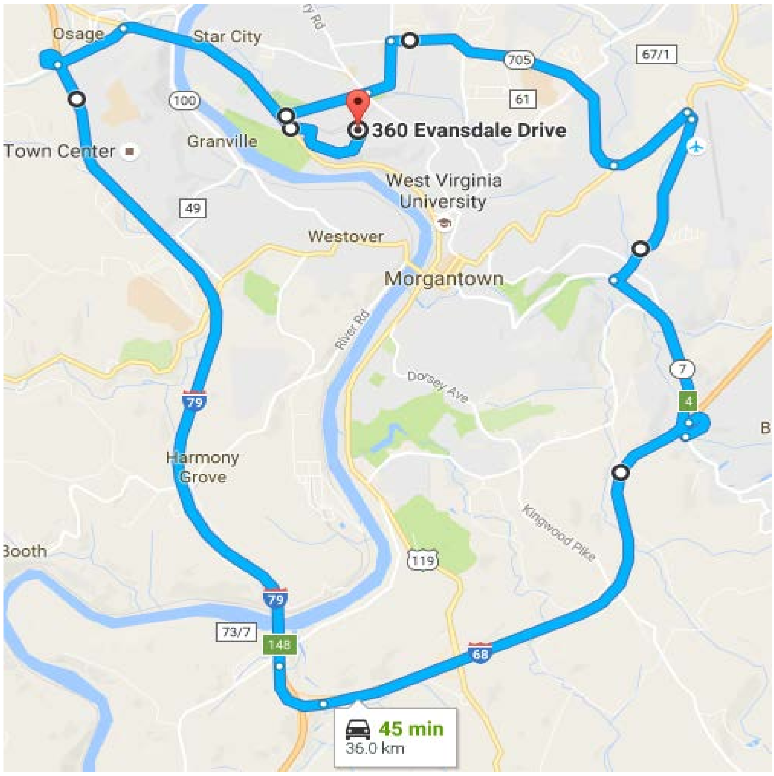

Figure 9 Geographic map of Route 1, rural and highway driving

Figure 10 shows the geographic map of route 2, the total distance is approximately 103 km with 70% of highway driving with uphill and downhill driving starting from exit 155 on I-79 South and headed back from exit 23 on I-68 East. This route started, ended at 360 Evansdale drive with highest elevation 683 meters above sea level, and lowest elevation being 260 meters above sea level.

Figure 11 shows the geographic map of route 3, the total distance is about 40 km with highway driving approximating to 20%. The altitude difference is approximately 125 meters to the highest and lowest elevations points. The route starts and ends at 163 Distributor drive, and this route has more traffic during noon than compared to other routes. This route takes on an average of 55 min without traffic.

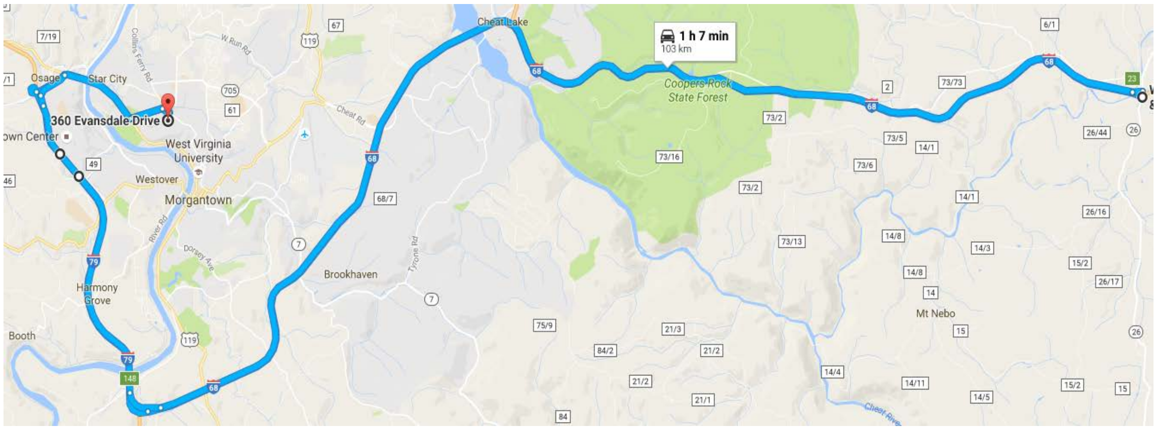

Figure 10 Geographic map of route 2, rural, highway and uphill/downhill driving

Figure 12 shows the geographic map of route 4, the total distance is about 80 km with highway driving approximately 78% of the total distance. The highest altitude is approximately 680 meters above sea level where as the lowest observed altitude is 275 meters approximately. This routes starts and ends at 163 Distributor drive same as the route 3.

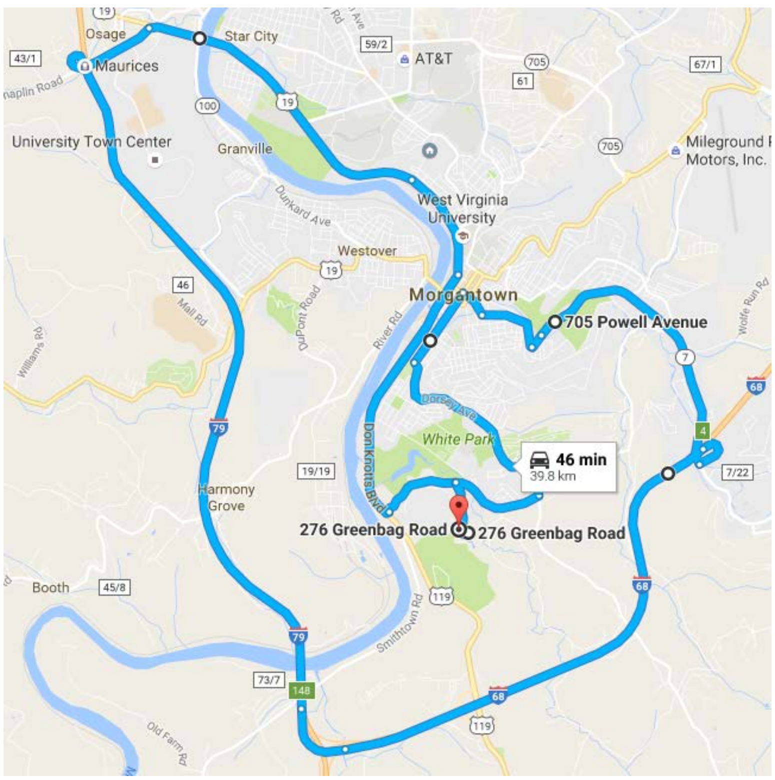

Figure 11 geographic map of route 3, urban, rural and highway driving

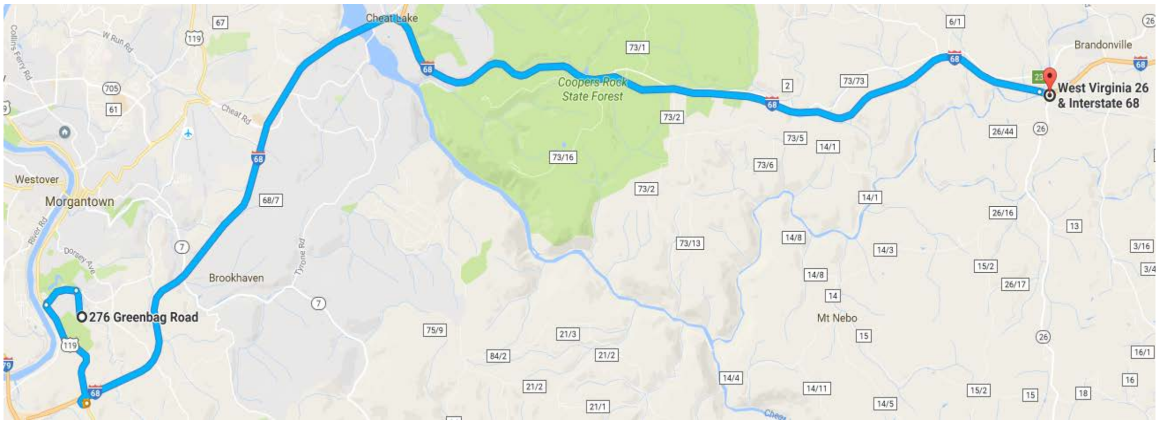

Figure 12 Geographic map of route 4, rural, highway and uphill/downhill driving

3.2.2 Pre-defined dynamometer test cycles

Four vehicles were tested on chassis dynamometer at Vehicle and Engines testing laboratory over three certification cycles (FTP-75, NEDC and US06), highway driving cycle (HWFET) and two custom made real world driving cycles (LA-4 and MGW). The characteristics of all these cycles has been discussed in Section 2.5of this report. The summary of these cycles can been seen in Table 3.4.

Table 3.4: Comparison of dynamometer cycles

Cycle	FTP-75	NEDC	US06	HWFET	LA-4	MGW
Cycle duration [sec]	1877	1180	596	765	2426	2410
Cycle distance [km]	17.77	10.93	12.89	16.45	25.1	35.90
Avg. vehicle speed [km/h]	34.08	33.35	77.84	77.7	37.3	53.63
Max. vehicle speed [km/h]	91.25	120.0	129.23	96.3	111.8	124.66
Avg. RPA [m/s^2]	0.23	0.15	0.52	0.18	0.32	0.27
Characteristic Power [m^2/s^3]	1.65	1.04	4.55	1.49	2.73	2.44
% Idling (≤ 2km/h)	20.40	25.08	8.17	0.91	21.5	16.89
% low speed (>2, ≤50 km/h)	58.50	43.31	17.67	4.44	42.8	33.69
% med speed (>50, ≤90 km/h)	19.50	24.41	17.83	71.41	28.0	27.76
% high speed (>90 km/h)	1.60	7.12	55.67	23.24	7.5	21.66

3.3 Emissions Testing Procedure and Equipment

The emissions sampling equipment used during this study consists of two sub-systems, one is to measure exhaust gas and other to measure particulate number. Figure 13 shows schematic of measurement test setup used for all vehicles. Exhaust gasses are measured using on-board emissions measurement system, OBS-One GS, from Horiba. Real-time particle number concentration are measured using Pegasor particle sensor (PPS), model PPS-M from Pegasor Ltd. PN is not a primary objective of this study, so it's not discussed in detail.

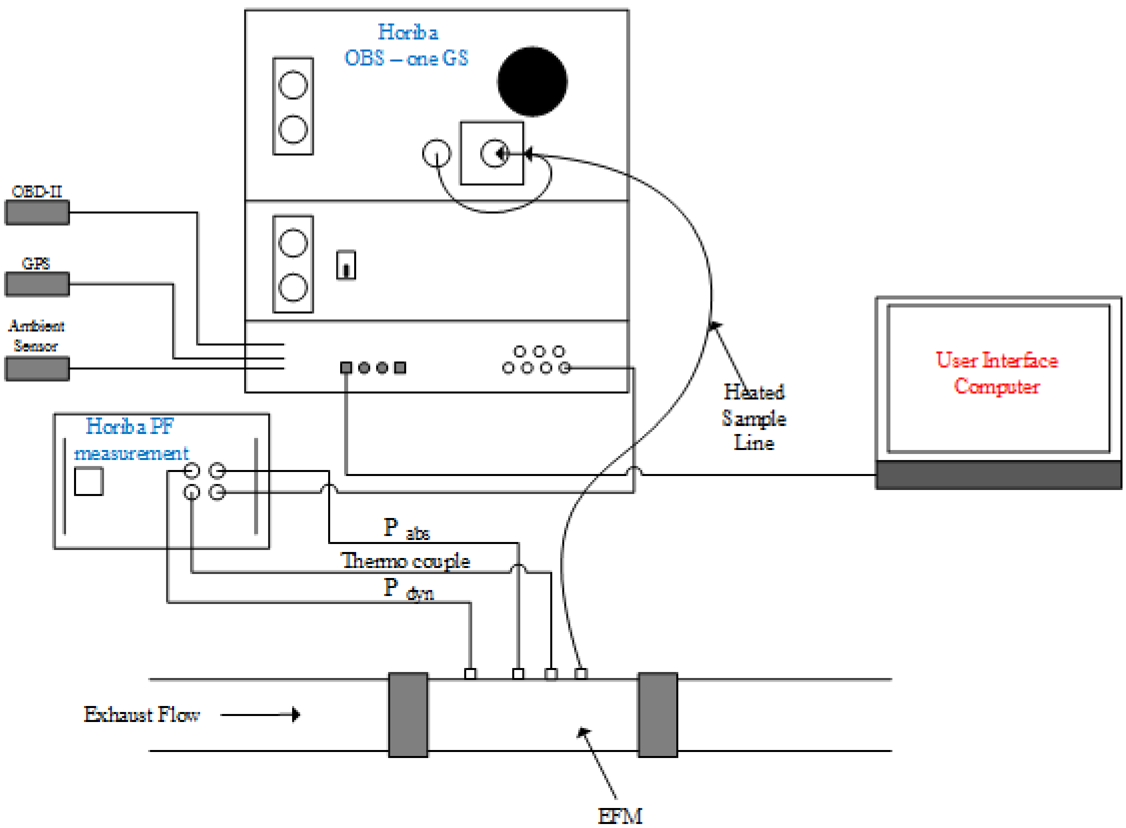

Figure 13 Schematic of measurement setup

OBS-one measurement system consists of one Non-Dispersive Infra-Red (NDIR) spectroscopy and two Chemi Luminescent Detector (CLD) analyzers to measure carbon and nitrogen components in the exhaust respectively. NDIR works on principle that CO and CO_2 absorbs infrared light of wavelength 4.26 µm. A chopper wheel with CO, CO_2 and reference filter is mounted in front of detector. The change in intensity of light is measured by thermopile. The difference intensity is directly proportional to number of CO and CO_2 molecules inside the analyzer (Shade 2000). Figure 14 is an image of NDIR cell along with Chopper Disk of filters.

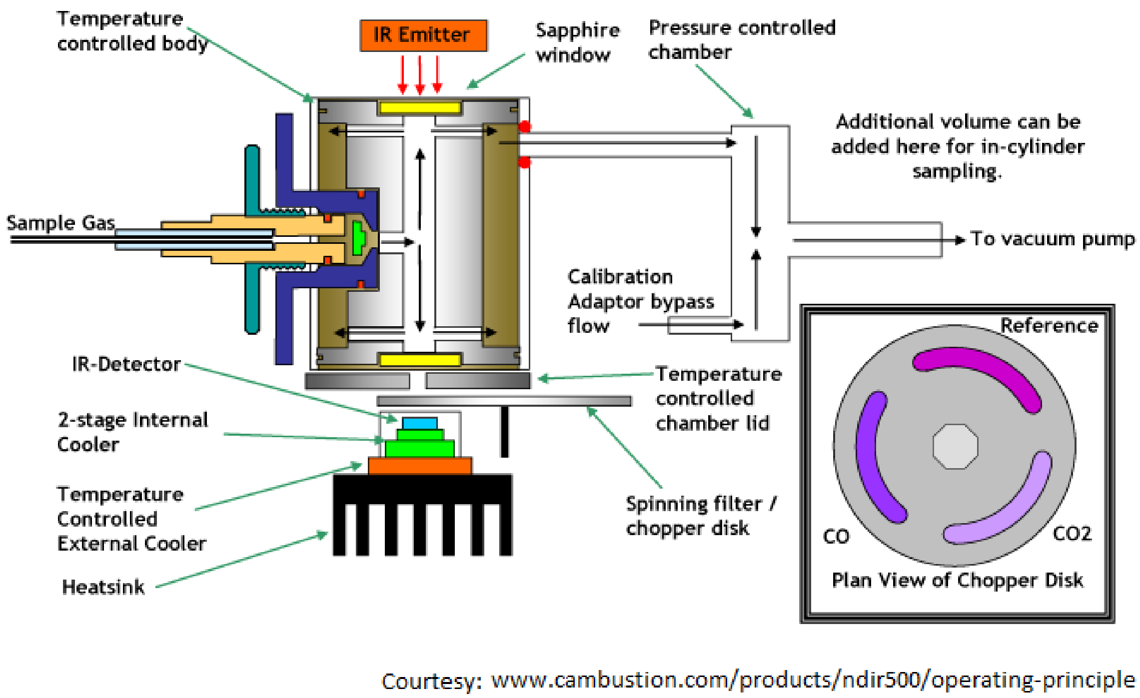

Figure 14: NDIR Cell

CLD (Chemi-luminescence Detector) analyzer is used to measure NO and NO_x, which produces photons when NO reacted with ozone. These photons are detected using photo multiplier tube (PMT), and the output voltage is proportional to concentration of NO inside the analyzer. OBS-one has two CLD analyzers, in which one measures NO directly while the other is used to measure NO_x by converting all NO_2 to NO and the difference of the measurement gives number of NO_2 molecules. (Shade 2000). Figure 15 is a schematic of CLD analyzer, while Figure 16 is a schematic of CLD analyzers in OBS-One.

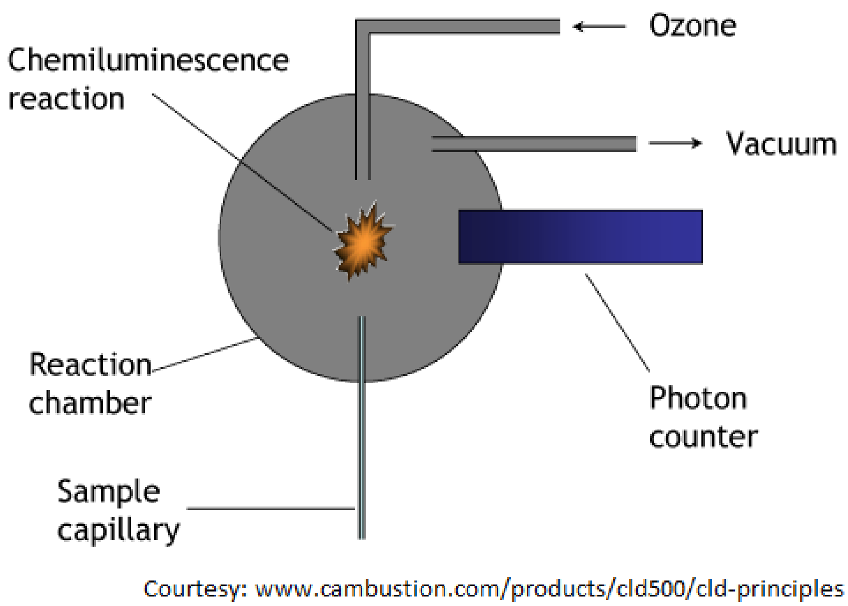

Figure 15: CLD Analyzer

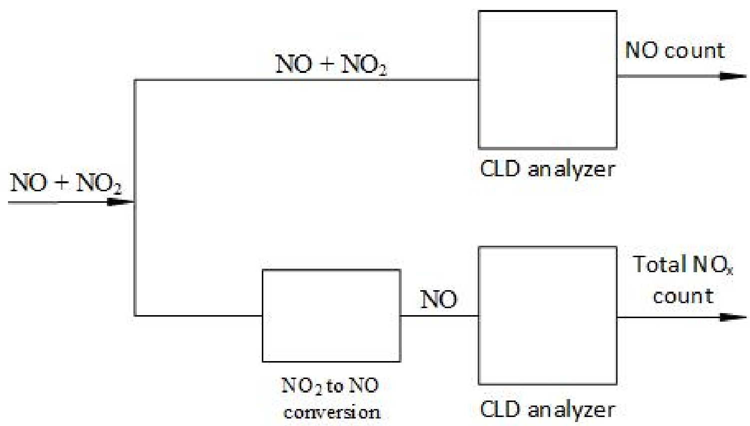

Figure 16 Schematic of CLD analyzers in OBS one

Table 3.5 lists of all parameters that have been measured during the test. Emission parameters are sampled and stored continuously at 10 Hz frequency whereas Engine Control Unit (ECU) and Global Positioning System (GPS) data is updated at 1 Hz but stored at 10 Hz frequency by data acquisition systems. Emission parameters are directly sampled by OBS-One through heated sample line from flow meter connected to exhaust. Two external sensors (GPS sensor, ambient temperature/ humidity sensor) are connected to data acquisition system. GPS receiver is used to measure relative speed, latitude, longitude and altitude. Ambient temperature / humidity sensor gives ambient conditions including temperature, barometric pressure and relative humidity. Exhaust flow is measured using pitot flow tubes from the flow meter. K-type thermocouple is used to measure exhaust gas temperature. Engine specific parameters are recorded from OBD-II port of the vehicle through OBD-II adaptor provided by Horiba along with OBS-one.

Table 3.5 List of measured parameters and respective instruments/analyzers

Category	Parameter	Measurement Technique
Exhaust gas pollutants	CO [ppm]	NDIR (Horiba OBS-one)
	CO2 [ppm]	NDIR (Horiba OBS-one)
	NOx [ppm]	CLD (Horiba OBS-one)
Exhaust flow	Exhaust flow rate [m3/min]	PF (Horiba OBS-one)
	Exhaust temperature [oC]	PF (Horiba OBS-one)
	Exhaust absolute pressure [kPa]	PF (Horiba OBS-one)
Exhaust PN/PM emissions	PN concentration [#/cm3]	Pegasor Particle Sensor
Ambient conditions	Ambient temperature [oC]	Temp. Sensor (OBS-one)
	Ambient humidity [%]	Humidity Sensor (OBS-one)
	Barometric Pressure [kPa]	Pressure Sensor (OBS-one)
Vehicle/route characteristics	Vehicle speed [km/h]	GPS
	Vehicle position [o]	GPS
	Vehicle altitude [m a.s.l]	GPS
	Vehicle acceleration [m/s2]	Derived from GPS data
	Vehicle distance traveled [km]	Derived from GPS data
Engine performance	Engine speed [rpm]	ECU OBD-II
	Engine load [%]	ECU OBD-II
	Engine coolant temperature [oC]	ECU OBD-II
	Engine intake air flow [kg/min]	ECU OBD-II
	Exhaust temperature [oC]	ECU OBD-II

Experimental setup and instrument arrangement inside the test vehicles A, B, C and D can be seen in Figure 17, Figure 18. For on-road testing, sampling instrument (OBS-One) and its related accessories including air and gas bottles, compressor to supply dry air for PN measurement device, generator to meet power demands by the instruments are payload weighing approximately about 300kg other than driver and passenger. This payload is not installed on the vehicle while testing them on chassis dynamometer.

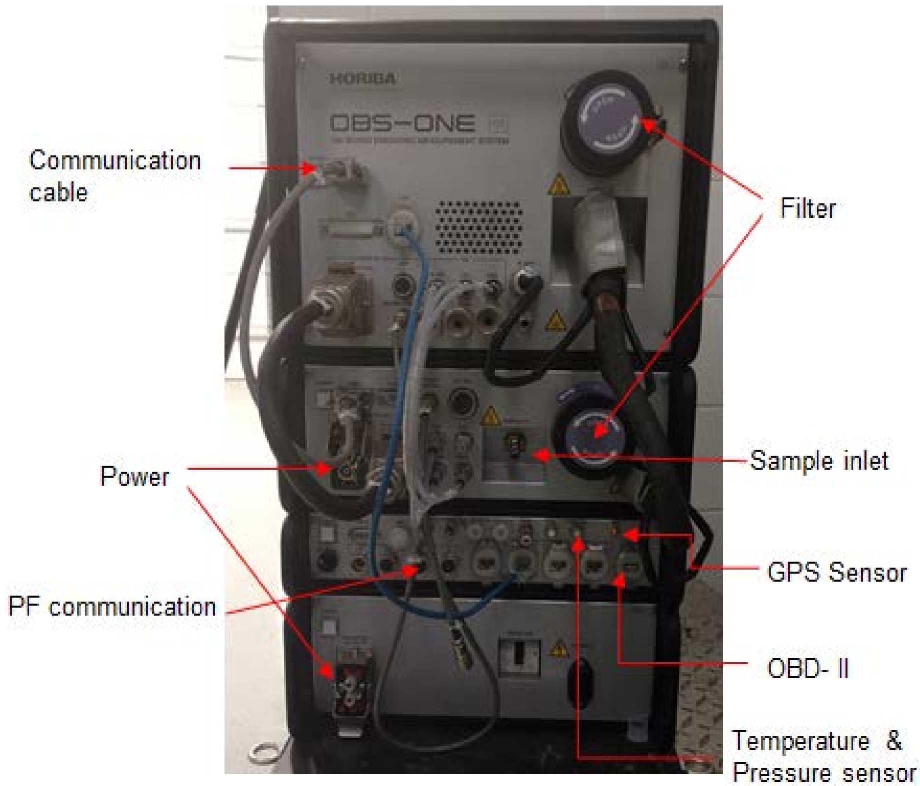

Figure 17 Measurement device setup

3.4 Emissions Sampling – Horiba OBS-one

OBS-One is a Portable Emission Measurement System manufactured by Horiba as per regulations mentioned in 40 CFR Part 1065. Exhaust gases are collected through a sample line, which is maintained at 191^{o}C to prevent gases condensing in the sample line. CO and CO_2 are measured using Non-Dispersive Infrared (NDIR) spectrometer, and NO_x is measured using Chemi-luminescence Detector (CLD) whose working principles are discussed earlier. Table 3.6 gives complete information regarding gasses measurement ranges and span values of each analyzer. These analyzers are calibrated and is tested for linearity.

Figure 18 Instrumentation setup

Table 3.6: Horiba OBS-one, Gaseous analyzer specifications

Component	**Range**	**Span**	**Linearity**	**Accuracy**
CO	10%	0.10%	within ±1.0% of full scale	within ±2.5% of full scale
CO_2	20%	12.5%	within ±1.0% of full scale	within ±2.5% of full scale
NO	3000ppm	1396ppm	within ±1.0% of full scale	within ±2.5% of full scale
NO_x	3000ppm	1396ppm	within ±1.0% of full scale	within ±2.5% of full scale

Emissions are collected through ½” National Pipe Thread Taper standard port installed on 2” diameter Exhaust Flow Meter (EFM) adapter mounted to exhaust end pipe. EFM has probes to measure flow rate by differential pressure and port for thermocouple to read exhaust gas temperature. The EFM used for all four vehicles during this study is shown in Figure 19. EFM installation, tail pipe adapter setup is similar for all *Vehicles* and can be seen in Figure 20

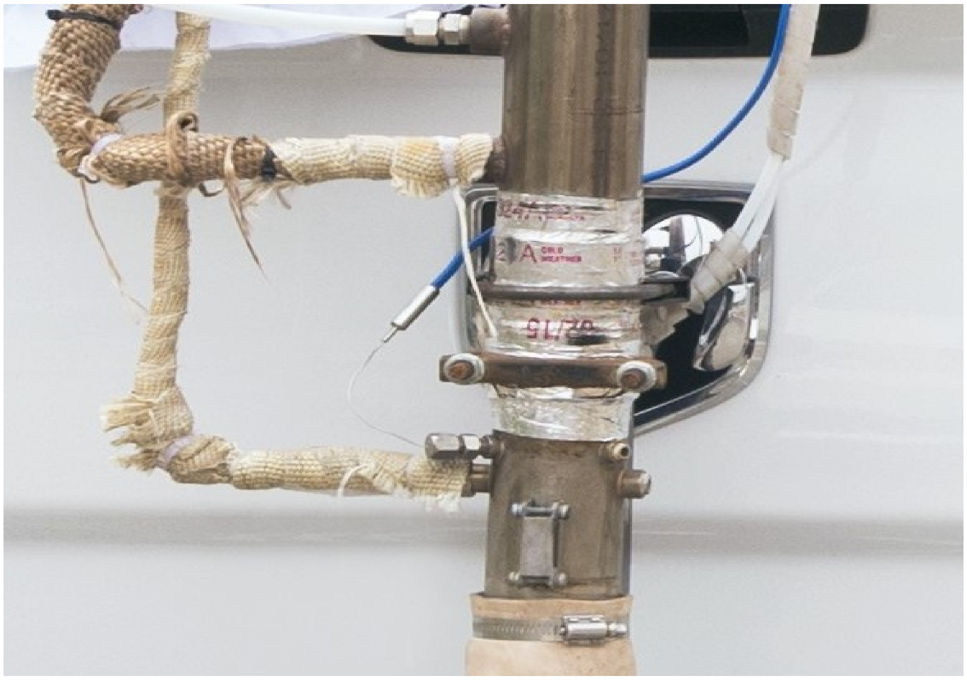

Figure 19 Exhaust Flow Meter [EFM]

Figure 20 Tail pipe adapter setup for all Vehicles

3.5 PEMS Installation and pre-test checks

3.5.1 PEMS Verification and Analyzer Checks

All measurement instruments used for this study is calibrated and verified as per regulations mentioned in CFR, Title 40, Part 1065, Subparts D and J. All the analyzers (CO, CO_2 and NO_x) are individually verified for linearity by passing calibration gas mixture and blended Nitrogen at 10 ratios equally spaced. Least squares regression analysis is performed between analyzer's response and theoretical calculations of calibration gas as per 40 CFR §1065.307.

All analyzers are checked for H_2O interference. In addition, heated sample line is checked for vacuum leak using a pressure calibration device and thermocouple using thermocouple calibrator. Table 3.7 shows list of analyzer checks performed and their pass criteria.

3.5.2 PEMS Installation and Testing

OBS is installed on test vehicles as shown in previous figures. Every day before the start of the test, the OBS is warmed-up until it is stabilized thermally. After warm up and before testing on a route, "*zero*" and "*span*" checks were performed and these checks are automated during the test.

Table 3.7 Analyzer checks and their pass criteria

Check	Analyzer	Method	Pass Criteria
Gas analyzer linearity	CO – NDIR, CO_2 – NDIR, NO & NO_x CLD	11 point Linear regression	$R^2 \geq 0.998$
H_2O interference	CO_2 – NDIR	Arthematic mean of 30 sec data	0 ± 0.4 mmol/mol
CO_2 & H_2O interference	CO – NDIR	Arthematic mean of 30 sec data	Within ± 2%
CO_2 & H_2O quench	CLD	Arthematic mean of 30 sec data	Within ± 2%
NO_2 to NO conversion efficiency	Ozone generator	Efficiency	≥ 95%

OBS performs "*zero*" and "*span*" checks and adjustments before and immediately after sampling. Analyzer drift values are recorded automatically by OBS to perform drift correction while calculating results.

3.6 Chassis Dynamometer and setup

Chassis Dynamometer coast-down is performed before and after each vehicle is fixed on dyno for testing. Coast-down is a procedure performed to account for aerodynamic drag, rolling resistance, axle and transmission spinning losses etc. Coast-down on chassis dynamometer is performed to reproduce the road load force at various speeds assuming a flat road.

$$F_{total} = A + Bv + Cv^2 + M\frac{dv}{dt} \qquad \textit{Eq. (17)}$$

$$F_{road\ load} = -M\frac{dv}{dt} = A + Bv + Cv^2 \qquad \textit{Eq. (18)}$$

The coefficients A, B and C from the road load equation is calculated by linear regression of vehicle velocity relative to wind as a function of time. These coefficients are given to dynamometer controller as target coefficients. Coast-downs on dynamometer are performed to produce same road load curve, which does not match in the first run as the dynamometer losses are not accounted. So the coast-downs are now iterated such that calculated forces in all speed ranges are within tolerance of ±10 N after a least square regression of forces for three consecutive coast-down adjusting the load coefficients previously used by changing the resistance applied on rollers. The coefficients at which load curve on the chassis is within ±0.05% of road load curve are used as set coefficients for further tests on dynamometer (40 CFR §1066.210). The target coefficients and set coefficients used for chassis dynamometer during this study are listed in Table 3.8 .

Table 3.8 Chassis Dynamometer Coefficients from EPA

Vehicle	ETW [lbs.]	Set Coefficients			Target Coefficients		
		A [lbf]	B [lbf/mph]	C [lbf/mph^2]	A [lbf]	B [lbf/mph]	C [lbf/mph^2]
A	6000	11.01	0.3262	0.03264	51.33	0.0451	0.0385
B	6000	11.01	0.3262	0.03264	51.33	0.0451	0.0385
C	6000	11.01	0.3262	0.03264	51.33	0.0451	0.0385
D	6000	11.01	0.3262	0.03264	51.33	0.0451	0.0385

3.7 Data analysis and calculations

Data analysis and its quality assurance used in this report follows recommendations mentioned in CFR, Title 40 Subpart 1065 D, G, and J. Emissions calculations along with drift correction and distance specific emission rates are done according to regulations outlined in CFR, Title 40 Subpart 1065 G. All tests with DPF regeneration events, and those aborted due to failure of any measurement system are invalidated.

4 Results and Discussion

This chapter presents data collected from test both on-road and chassis dynamometer. It will also discuss the average on-road emissions from all four-test vehicles for the pre-defined test routes, followed by in depth analysis of the NO_x emissions.

In this, report all the emissions mass rates are in [g/s]. Distance-specific emissions [g/km], work-specific emissions [g/bhp-hr] are reported for each emission constituent, which is average of total measure with total distance and total work done during the test respectively. Applicable regulatory emission limits for NO_x, CO and CO_2 is mentioned in the following table.

Table 4.1 EPA Vehicle Certification standard

Vehicles	**Certification**	**CO**		**CO_2**		**NO_x**		**Fuel Economy**	
		[g/km]	[g/mile]	[g/km]	[g/mile]	[g/km]	[g/mile]	[kmpl]	[mpg]
A	FTP-75	0.1040	0.1675	239.45	385.37	0.0274	0.0442	11.22	26.4
B, C & D		0.0577	0.0929	258.05	415.30	0.0203	0.0328	10.46	24.6
A	HWFET	0.0080	0.0129	169.07	272.1	0.0180	0.0289	17.43	41
B, C & D		0.00039	0.00064	169.07	272.1	0.0180	0.0289	15.9	37.4

All four vehicles are not tested in all four pre-defined routes. Routes 1 and 3 resemble by more than 70% except with an additional urban driving for route 3 and is referred as Morgantown route hereafter, while Routes 2 and 4 resemble by 80% in terms of road grade elevation and highway speeds except the total distance is less by 20 km in route 4 than route 2 and is referred as Bruceton route. Morgantown routes and Bruceton routes are shown in Figure 21 and Figure 22 respectively.

All emission rates mentioned from here on are in terms of grams per kilometer [g/km]. Elevation is discussed in terms of meters above sea level [m a.s.l]. More discussion about these routes and their influence in total emissions are discussed in later sections of this chapter.

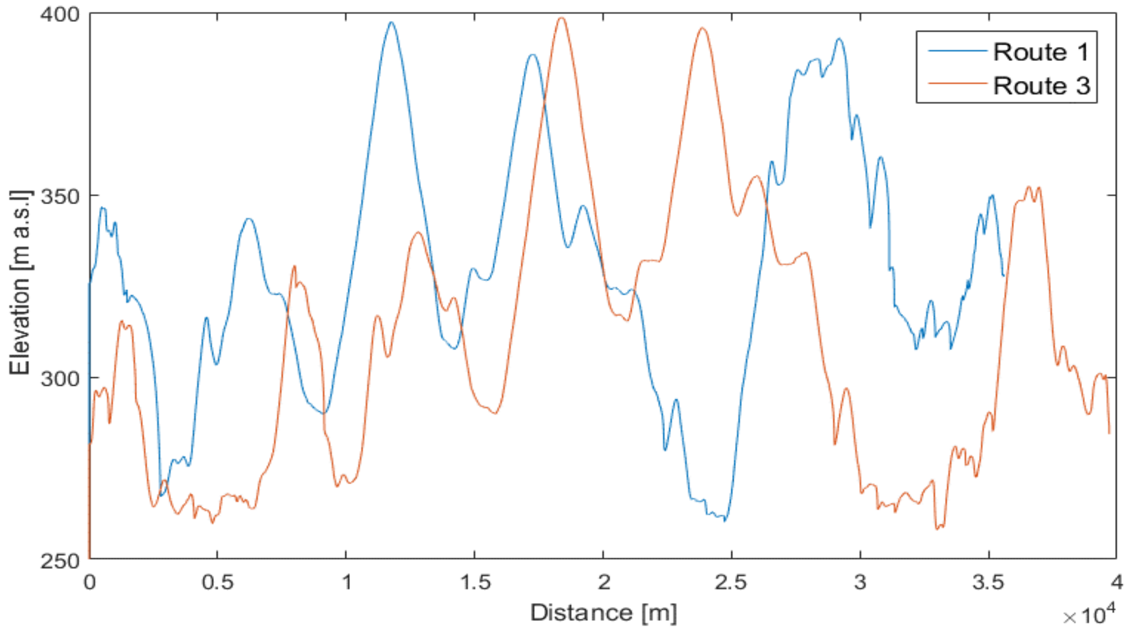

Figure 21 Morgantown on-road routes

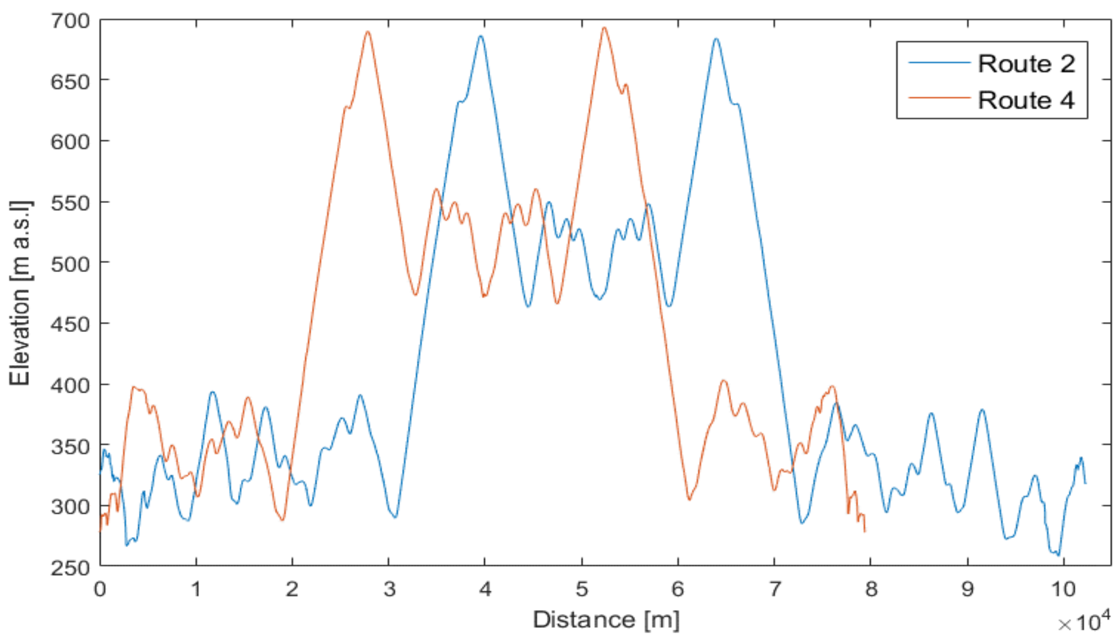

Figure 22 Bruceton on-road routes

Cold start, hot start and Warm start are three types of tests which indicate 12 hours of soak, key on with engine running, key off with engine stopped running before the tests respectively. Type of the test is attached as a suffix to the name of the test route.

Number of runs each vehicle was tested in different routes both on-road and chassis dynamometer are listed in Table 4.2 and Table 4.3 respectively. A minimum of three repetitions of each test is done on-road whereas a minimum of two repetitions of each driving cycle is done on chassis dynamometer, but all of the repetitions are not considered due to poor quality of measured data or other issues with the measuring instrument during the test.

Table 4.2 On-road test matrix

	Vehicle A	**Vehicle B**	**Vehicle C**	**Vehicle D**
Route 1	7	11	-	-
Route 2	4	5	-	-
Route 3	-	-	7	5
Route 4	-	-	6	3

Table 4.3 Chassis Dynamometer test matrix

Cycles	**Vehicle A**	**Vehicle B**	**Vehicle C**	**Vehicle D**
FTP-75	4	3	5	5
NEDC	1	2	2	2
US06	1	-	1	2
HWFET	1	-	3	2
LA-4	1	-	2	2
MGW	2	2	2	2

DPF regeneration events that occurred during the test are identified with increased concentrations of particulate number measured using Pegasor-M, associated with increased exhaust temperatures and high NO_x. All DPF regen events occurred in four vehicles during the test are listed in the following Table 4.4. ECU data is lost for Regen event occurred during FTP-75 test of Vehicle A. So, this event is discarded.

Table 4.4 DPF regen event

	On-road route	Chassis
Vehicle A	-	NEDC(1)
Vehicle B	Route 1(2) , Route 2(1)	-
Vehicle C	-	FTP-75(1),US06(1)
Vehicle D	Route 3(3), Route 4(1)	MGW(1)

4.1 Average On-Road Emissions of Light Duty Vehicles

This section will present average on-road emissions factors for gaseous, including NO_x, CO and CO_2 emissions as measured for four vehicles over pre-defined test routes. Results presented in this section are reported as total emission over the respective routes.

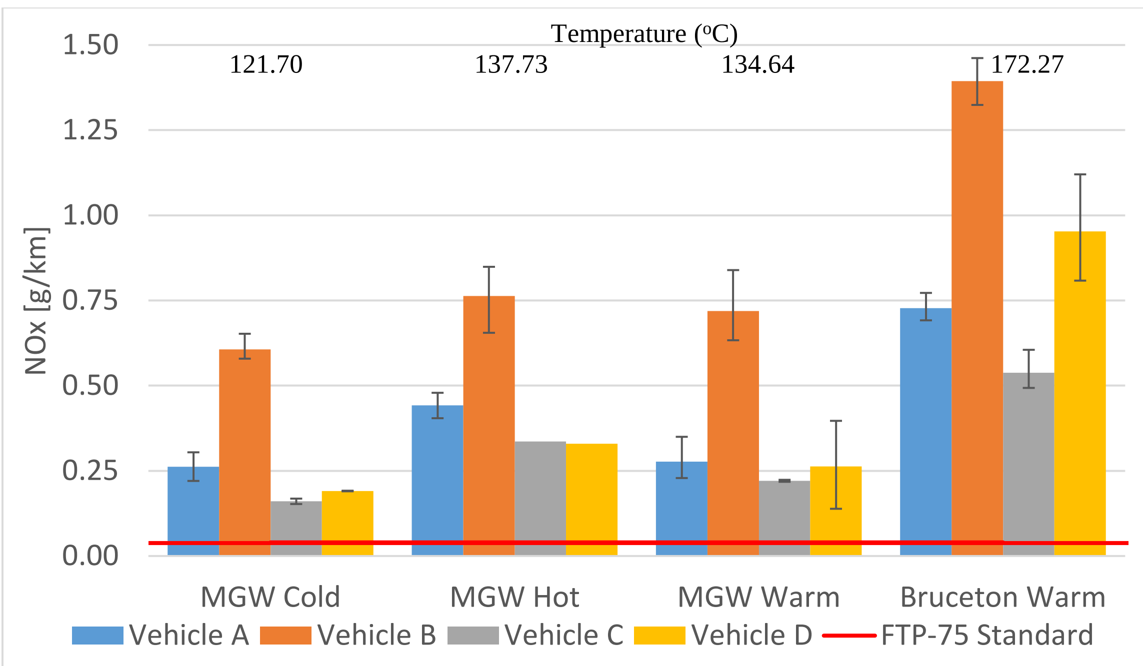

Figure 23 Average NO_x Emissions

Figure 23 shows average on-road NO_x emissions for Vehicles A, B, C and D measured in routes 1 to 4 as explained above. Table 4.5 shows average NO_x emissions along with standard deviations computed over at least two repetitions of a given test in a given vehicles.

Usually high NO_x is observed in uphill/downhill and low for highway driving. Here in this report all four vehicles showed distinct NO_x levels in all routes, Vehicle B exhibiting about 8 to 20 times more than Tier2-Bin5 NO_x standards whereas other vehicles exhibiting about 3 to 13 times. All vehicles exhibited more NO_x during uphill/downhill driving compared to other driving routes. Vehicle C exhibited low NO_x throughout the testing, even at uphill/downhill driving average NO_x is about 0.53 g/km (~7 times) the standard.

Although, all the vehicles are outfitted with engine from same manufacturer and have same rated power, engine of Vehicle A belongs to a different Model year and family from the others. Though all the vehicles use similar after treatment technologies, they exhibit different NO_x levels for same test routes. This might be due to many reasons like i) different after-treatment control strategies, ii) a difference in catalytic substrate, iii) different diesel exhaust fluid (DEF) injection strategy and iv) reduction in catalytic activity due to aging.

All vehicles are checked for possible Malfunction Illumination Light on the dashboard, an ECU scanning tool is also used to log any malfunction code prior to test of these vehicles and none have shown any codes related to after-treatment systems.

Table 4.5 Average NO_x emissions [g/km]

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
Morgantown Cold	0.262	0.059	0.606	0.040	0.160	0.011	0.190	0.001
Morgantown Hot	0.441	0.052	0.763	0.098	0.336	-	0.329	-
Morgantown Warm	0.276	0.064	0.718	0.074	0.220	0.004	0.262	0.105
Bruceton Warm	0.727	0.033	1.394	0.054	0.537	0.059	0.952	0.108

Figure 24 shows average CO_2 emissions from Vehicles A to D measured over four pre-defined routes. Average emissions along with the standard deviations computed at least over two repetitions of given test are summarized in Table 4.6

Table 4.6 Average CO_2 Emissions

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
Morgantown Cold	293.1	2.870	267.8	8.285	262.5	8.029	268.7	9.631
Morgantown Hot	275.6	31.86	256.1	16.21	277.8	-	262.5	-
Morgantown Warm	277.8	19.85	267.3	4.857	247.5	7.140	266.8	7.421
Bruceton Warm	259.5	5.363	253.7	5.990	254.3	1.426	274.1	4.442

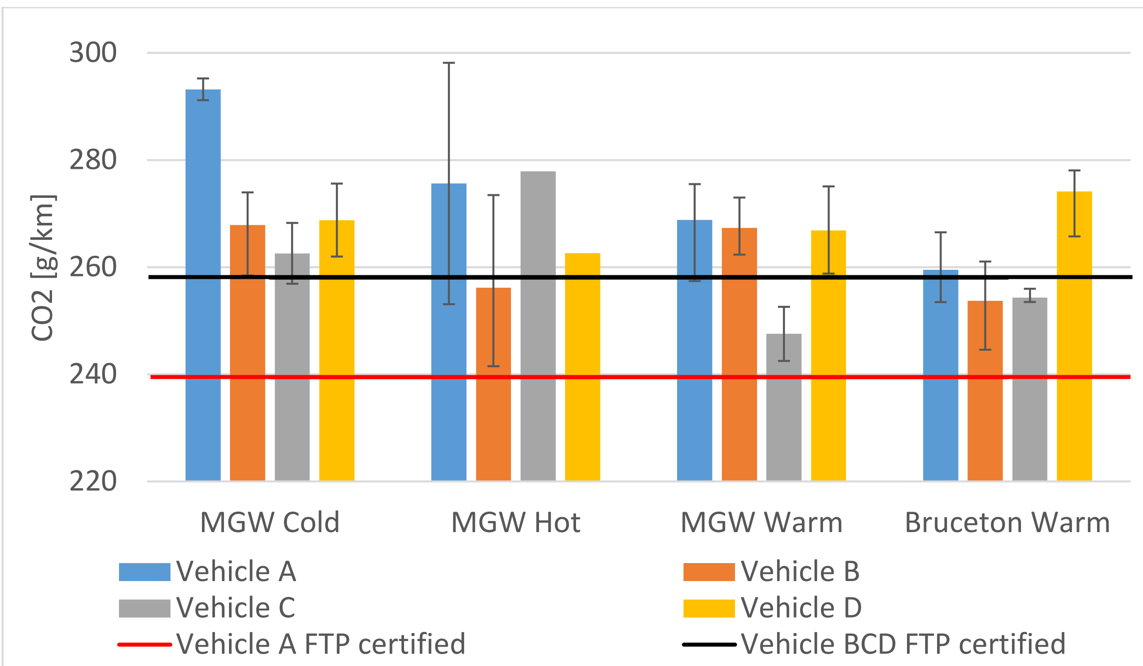

Figure 24 Average CO_2 Emissions

It is interesting to observe that Vehicle B which emitted high NO_x through-out does not follow same trend in CO_2 emissions. CO_2 emissions from all vehicles are in range of 245 to 295 g/km, with standard deviations from all vehicles less than 10 g/km except for hot start. Usually higher emission rates appear in routes with higher grade elevations, but Bruceton route which have an elevation difference of 400 m produced same average CO_2 emissions. This might be due to extent of highway distance in the route and very less urban speed distance.

Table 4.7 summarize the average CO emissions from four vehicles tested over predefined test routes along with standard deviations calculated from repetitions. Figure 25 shows the averaged emission rates with the error plots calculated from standard deviations.

Table 4.7Average CO Emissions

Routes	**Vehicle A**		**Vehicle B**		**Vehicle C**		**Vehicle D**	
	μ	σ	μ	σ	μ	σ	μ	σ
Morgantown Cold	0.107	0.035	0.224	0.024	0.358	0.015	0.304	0.069
Morgantown Hot	0.033	0.001	0.145	0.054	0.154	-	0.169	-
Morgantown Warm	0.064	0.035	0.139	0.009	0.136	0.054	0.176	0.021
Bruceton Warm	0.040	0.005	0.157	0.009	0.128	0.027	0.197	0.031

In general CO emissions are function of routes / driving conditions, which says vehicles follow the trend based on routes. But the observed emission rates from all vehicles are 8 to 75 lower than the FTP standard 2.6 g/km. *Vehicle A* produced lowest CO emissions of all, in all routes. This could be due because of advanced combustion strategy as it equipped with new MY engine and from other engine family. All vehicles exhibited more CO emissions during the cold start while they were reduced for later tests. Interestingly *Vehicle C* which produced CO emissions about 0.35 g/km during cold start dropped it by half for hot start and warm starts.

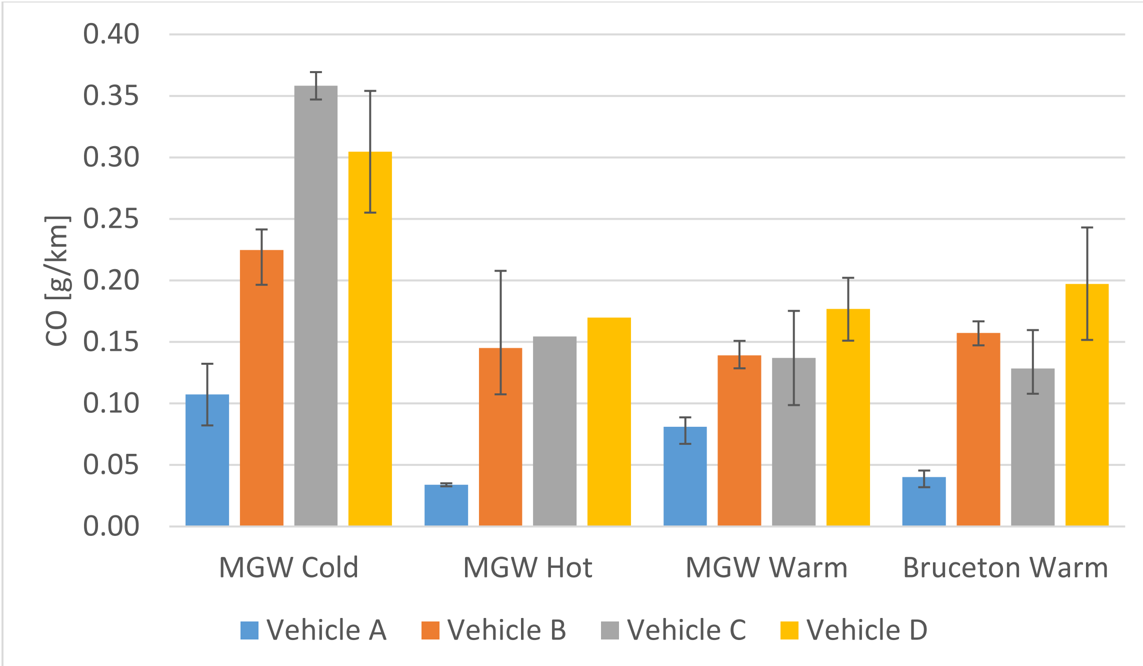

Figure 25 Average CO Emissions

Figure 26 shows the Average Fuel Economies presented in mpg, derived from carbon balance in four pre-defined test routes. And Table 4.8 summarizes Fuel economies along with standard deviations calculated for test with minimum of two repetitions.

As CO_2 is major fraction in carbon balance calculation, more the CO_2 emissions more fuel is consumed over the specified route. As CO_2 emissions were discussed earlier, observations are valid for low fuel economy too. All vehicles gave Fuel Economy ranging from 23-25 mpg in route 2 & 4 which consists both highway and uphill/downhill driving. Vehicles A and C show a reduction of Fuel economy by 5 % in cold start from warm start, whereas Vehicle B and D show less than 1% reduction.

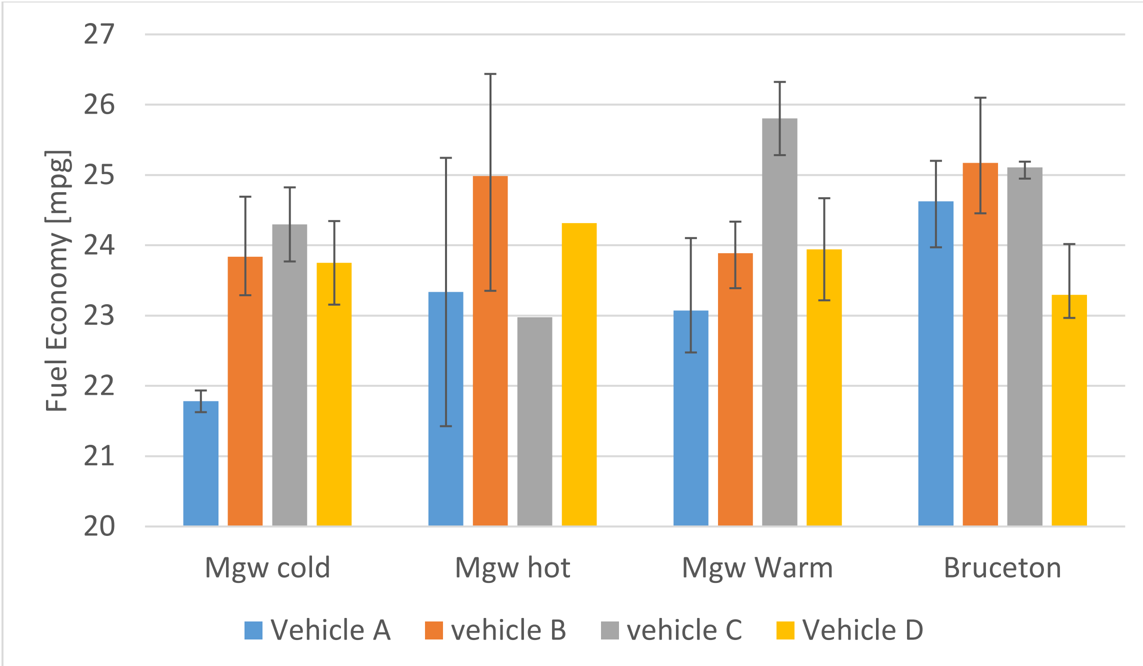

Figure 26 Average Fuel Economies derived from Carbon Balance

It's interesting to observe that Vehicle B which produced more NO_x than other vehicles in all routes, produced low CO_2 emissions and showed high fuel economy. This could be due to strategies employed to gain fuel economy than to reduce NO_x. Test done on chassis dynamometer discussed in next section will give more information.

Table 4.8 Average Fuel Economies derived from Carbon Balance [mpg]

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
Morgantown Cold	21.7	0.217	23.8	0.749	24.9	0.745	23.7	0.84
Morgantown Hot	23.3	2.699	24.9	1.550	22.9	-	24.3	-
Morgantown Warm	23.0	1.595	23.8	0.432	25.8	0.736	23.9	1.02
Bruceton Warm	24.6	0.505	25.1	0.600	25.1	0.138	23.2	0.38

4.2 Average Emissions from chassis dynamometer

This section will present average chassis dynamometer tests performed at VETL CAFEE, WVU. The emissions factors for gaseous, including NO_x, CO and CO_2 emissions measured for four vehicles over pre-defined driving cycles are presented in this section are reported as total emission in grams over the respective driving cycles in km.

Figure 27 shows average NO_x emissions from six chassis dynamometer driving cycles. All tests performed on dynamometer are with engine warmed up, except for FTP which is done both on cold start and warm start. Table 4.9 summarizes average NO_x emissions from chassis dynamometer and standard deviations calculated for the tests with minimum of two repetitions.

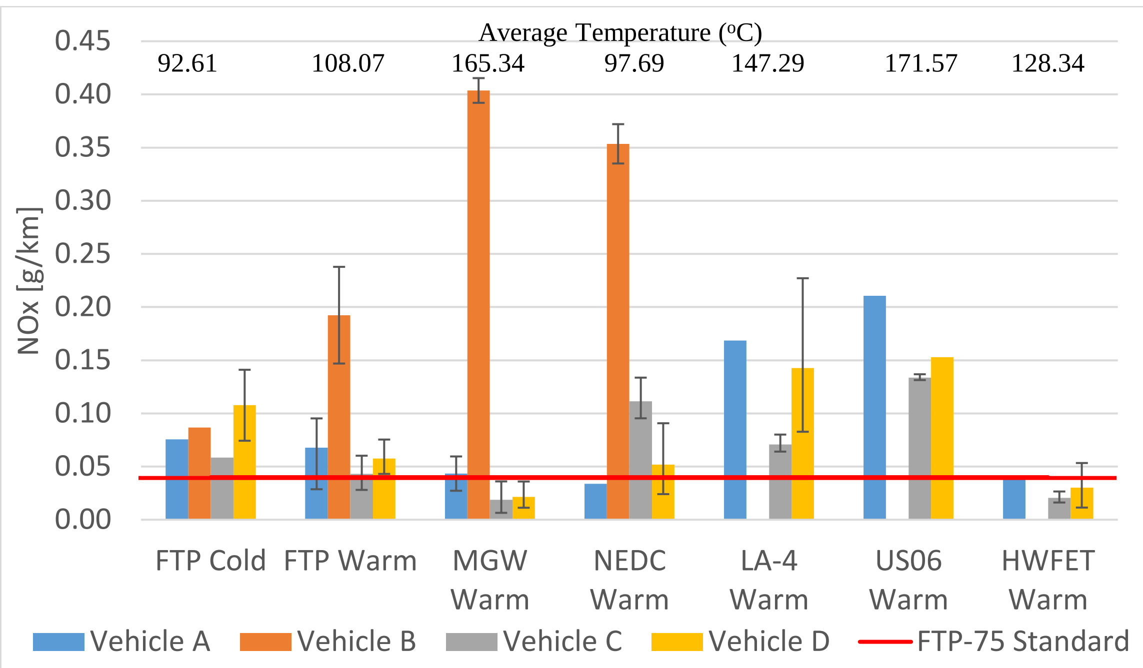

Figure 27 Average NO_x Emissions from Chassis Dynamometer

All the vehicles are certified with NO_x emissions less than FTP-75 standard of 0.04 g/km, but when tested on same driving cycle produced more than the standard. Their deviation ratios are in the range of 1-5 times the standard. *Vehicle C* is the only one which was close to standard in both cold and warm start. *Vehicle D* produced more NO_x in cold start whereas *Vehicle B* was the one to produce more during warm start.

If we consider Morgantown cycle which is a representative of route 1 of on-road tests, *vehicles A, C & D* produced 6-10 times lower than emissions from on-road tests. This could be because of 1) elevation/grade profile which is not accounted for in chassis cycle. 2) Traffic might be another reason which is not considered while creating the driving cycle.

In fact NO_x emissions from New European Driving Cycle should be low as this driving cycle is low speed and low load cycle. But, only *Vehicle A* and *Vehicle D* meet EU standard of 0.08 g/km over NEDC cycle, whereas *Vehicle B* is 5 times the standard while *Vehicle C* is slightly over the standard. Emissions from *Vehicle B* are not repetitive as the standard deviations are more than other vehicles and as emissions rates are high, further tests over chassis dynamometer that are required could not be performed.

Table 4.9 Average NO_x Emissions from chassis dynamometer

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
FTP Cold	0.07	-	0.08	-	0.05	-	0.10	0.03
FTP Warm	0.06	0.03	0.19	0.06	0.04	0.01	0.05	0.01
MGW Warm	0.04	0.02	0.40	0.01	0.01	0.01	0.02	0.01
NEDC Warm	0.03	-	0.35	0.02	0.11	0.02	0.05	0.03
LA-4 Warm	0.16	-	-	-	0.07	0.009	0.14	0.08
US06 Warm	0.21	-	-	-	0.13	0.003	0.15	-
HWFET Warm	0.03	-	-	-	0.02	0.006	0.03	0.02

Emissions from aggressive US06 cycle are ranging from 0.13 – 0.21 g/km which is 6 to 10 times the standard. Whereas in HWFET highway driving cycle shows reduction by ~40-50%

reduction than measured over FTP cycle. All these emissions were close to FTP-75 standards but slightly higher than their certification values.

CO_2 emissions which is direct measure of load and fuel consumption, measured over pre-defined dynamometer cycles is represented in Figure 28. Average CO_2 emissions measured in these cycles are summarized in Table 4.10. Standard deviations are calculated for the tests with minimum of two repetitions.

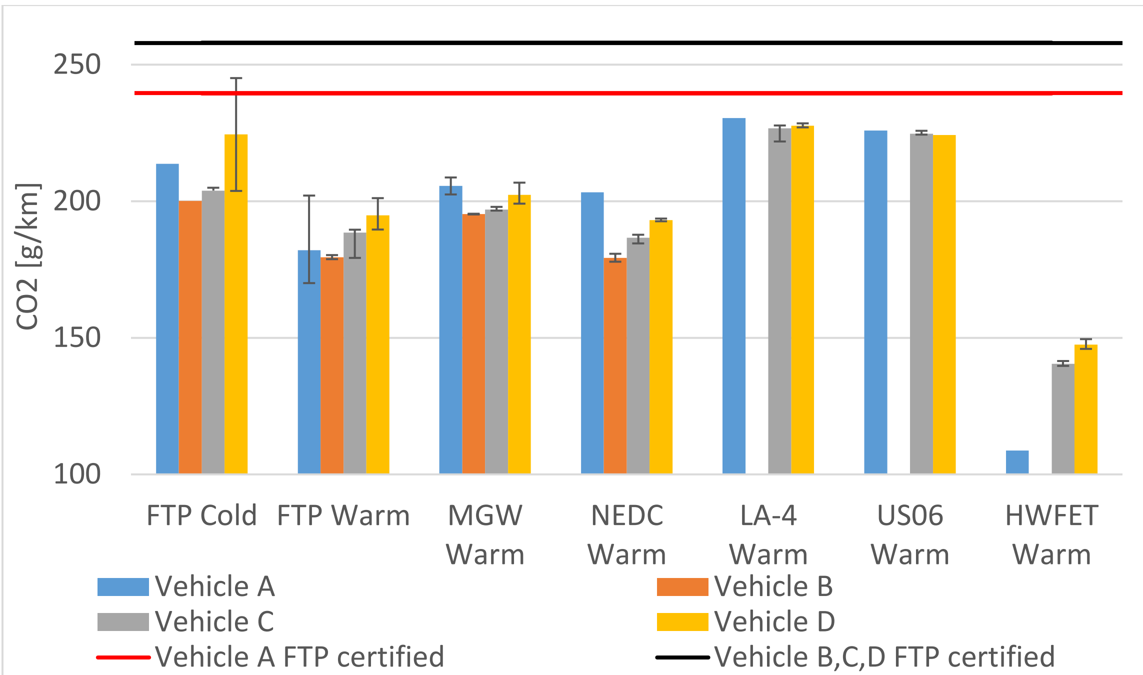

Figure 28 Average CO_2 Emissions from Chassis Dynamometer

CO_2 emissions from these vehicles doesn't follow the same trend as NO_x emissions. They are high in aggressive routes like LA-4 & US06, whereas low in high route HWFET. CO_2 emissions are high in cold start as similar to on-road measurements. After the Aftertreatment systems reached high enough the emission rates reduced by 7 – 15 % approximately.

CO_2 emission measured over Morgantown cycle are 20-25 % less than the measured on road. CO_2 emission rate from chassis Morgantown cycle ranges from 195 g/km to 205 g/km. Vehicles A to D follow the same trend of on-road emissions, but there were low because chassis cycle did not consider road grade elevation which is a major component and traffic.

Vehicle D produced CO_2 more than any other vehicle in all driving cycles, whereas *Vehicle B* produced low CO_2 among the four tested driving cycles. Vehicle A which produced more carbon dioxide emissions in aggressive and high speed cycles, also produced low emissions in highway driving cycle.

Table 4.10 Average CO_2 Emissions from Chassis Dynamometer

Routes	**Vehicle A**		**Vehicle B**		**Vehicle C**		**Vehicle D**	
	μ	σ	μ	σ	μ	σ	μ	σ
FTP Cold	213.7	-	200.0	-	203.8	-	224.4	20.6
FTP Warm	182.0	17.4	179.5	1.05	188.5	10.71	194.8	6.33
MGW Warm	205.5	4.3	195.2	0.18	196.8	0.45	202.2	4.50
NEDC Warm	203.2	-	179.3	2.05	186.6	3.0	193.0	0.57
LA-4 Warm	230.4	-	-	-	226.6	6.80	227.6	0.86
US06 Warm	225.9	-	-	-	224.7	0.50	224.2	-
HWFET Warm	108.7	-	-	-	140.4	1.04	147.5	1.96

Figure 29 Shows average CO emissions from all vehicles tested on chassis dynamometer testing cycles. And Table 4.11 summarizes these emissions in g/km with standard deviations calculated from a tests with minimum of two repetitions. CO emissions are high in cold start as they are in on-road cold start emissions. Once the catalysts reach their activation temperature, the emission are close to zero.

Vehicle D showed more CO production while *Vehicle A* produced low CO than other vehicles and it follows the same trend in all tests performed on dynamometer. All vehicles deviate the FTP CO standard by a ratio of 6 – 11 for FTP cold, 1 – 4 for other tests. Only *Vehicle A* showed emission less than its certification value over FTP cycle, while it was 6 times over the HWFET certification value. All other vehicles deviate their FTP certification value by 2 to 3 times, whereas

HWFET by 176 to 200 times. This could be because CO certification over HWFET was reported wrongly to EPA.

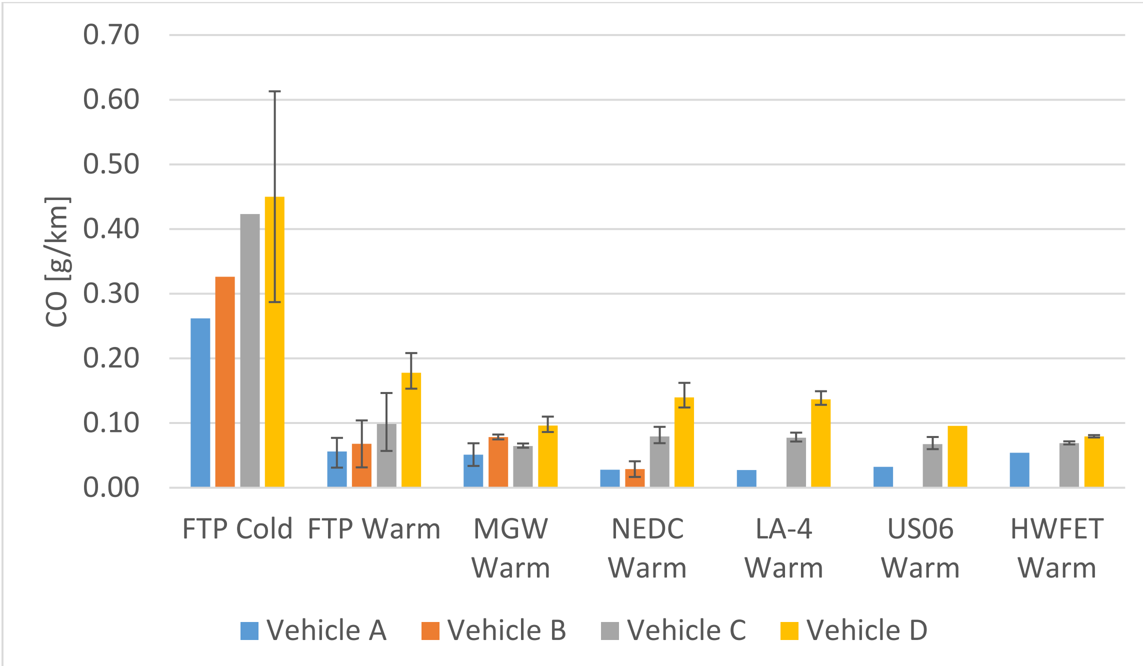

Figure 29 Average CO emissions from Chassis Dynamometer

Table 4.11Average CO emissions from Chassis Dynamometer

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
FTP Cold	0.26	-	0.32	-	0.42	-	0.45	0.06
FTP Warm	0.05	0.02	0.06	0.05	0.09	0.04	0.17	0.03
MGW Warm	0.05	0.02	0.07	0.00	0.06	0.00	0.09	0.01
NEDC Warm	0.02	-	0.02	0.1	0.07	0.01	0.13	0.02
LA-4 Warm	0.02	-	-	-	0.07	0.00	0.13	0.01
US06 Warm	0.03	-	-	-	0.06	0.01	0.09	-
HWFET Warm	0.05	-	-	-	0.06	0.00	0.07	0.00

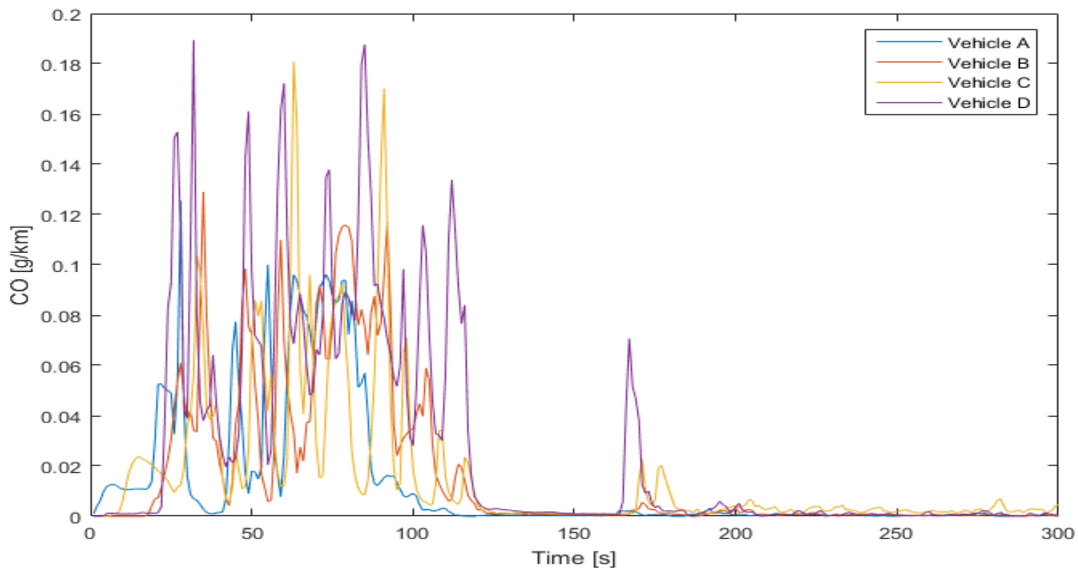

Figure 30 CO spikes during cold start

If we look at Figure 31, it's clear that fuel economy over chassis dynamometer is more than on-road tests. All vehicles clearly cross the fuel economy values reported to EPA over both FTP and HWFET cycles, even in cold start. Table 4.12 summarizes average fuel economy values obtained from carbon balance along with standard deviations measured from repetitions of two tests.

Table 4.12 Average fuel economy from carbon balance

Routes	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
	μ	σ	μ	σ	μ	σ	μ	σ
FTP Cold	29.8	-	31.8	-	31.2	-	28.5	2.64
FTP Warm	35.2	3.21	35.5	0.19	33.9	1.80	32.7	1.04
MGW Warm	31.0	0.67	32.6	0.02	32.4	0.07	31.5	0.70
NEDC Warm	31.4	-	35.6	0.41	34.2	0.54	33.0	0.09
LA-4 Warm	27.7	-	-	-	28.1	0.84	28.0	0.10
US06 Warm	28.2	-	-	-	28.4	0.06	28.4	-
HWFET Warm	58.7	-	-	-	45.4	0.33	43.2	0.57

As fuel economy is a direct measure from obtained CO_2 and is inverse proportional to CO_2. All vehicles gave fuel economy greater than 30 mpg in regular certification cycles and little lower of 28 mpg in aggressive cycles like LA-4 and US06, and highest economy of 43 mpg in highway driving cycle. *Vehicle A* showed highest economy of 58 mpg in highway driving cycles as it was run on double HWFET cycle continuously without stopping the sampling.

All *Vehicles A, C and D* gave a fuel economy more than 43 mpg over HWFET cycle, which is approximately two times more than that is observed in highway driving of Bruceton route. Quality of data has been checked, and found no loss in exhaust sampling, no fault in measurement device. EPA data sheet shows that manufacturers reported about 41 mpg on HWFET cycle, which also supports the fact that the quality of data provided in this research is good.

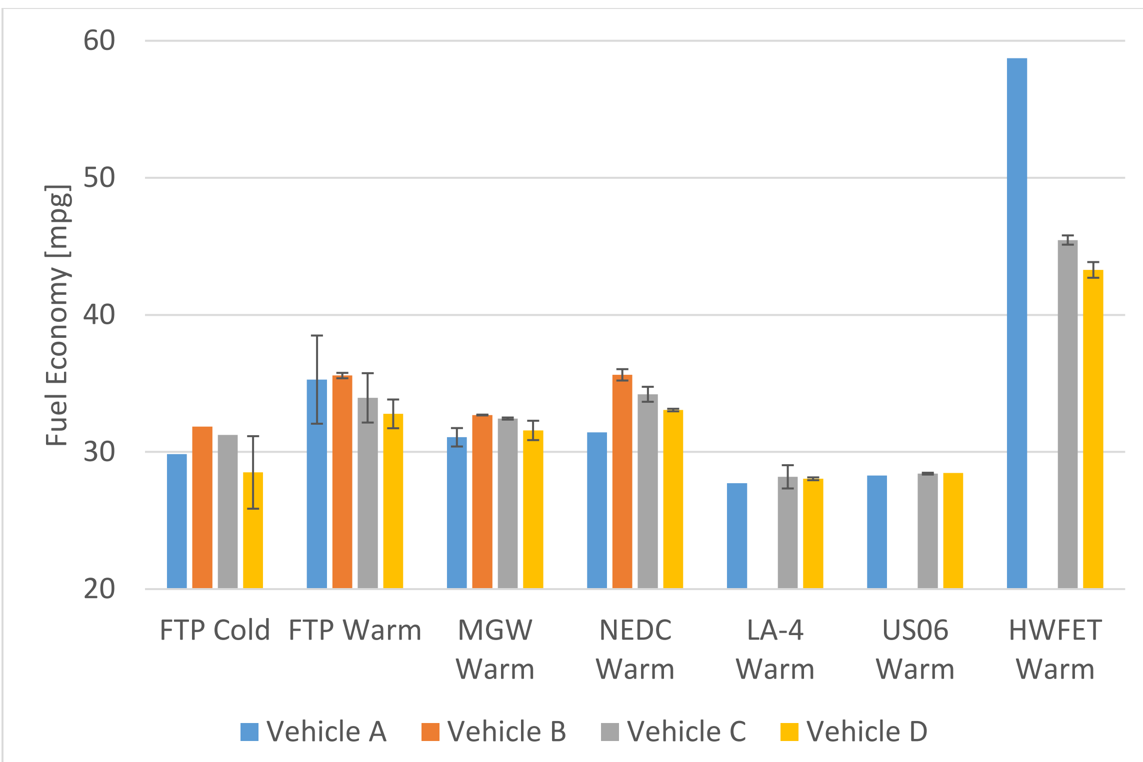

Figure 31 Average fuel economy from carbon balance

4.3 Comparison of NO_x from On-road measurements to Chassis Dynamometer cycle measurements

Earlier sections show a comparison between emissions rates & fuel economy rates of four vehicles tested in different on-road routes and chassis dynamometer cycles. Comparisons among these on-road routes and chassis cycles show only variations between the vehicles but, this section shows comparison of NO_x and Fuel Economy (FE) rates between similar on-road routes and chassis cycles.

4.3.1 Morgantown on-road route comparison with Morgantown chassis cycle

In this section, Morgantown on-road cycle NO_x emission rates are compared with Morgantown chassis cycle emissions. Morgantown chassis cycle resembles on-road route as it is created from real driving speed points from on-road route, and this can be used as common base to compare.

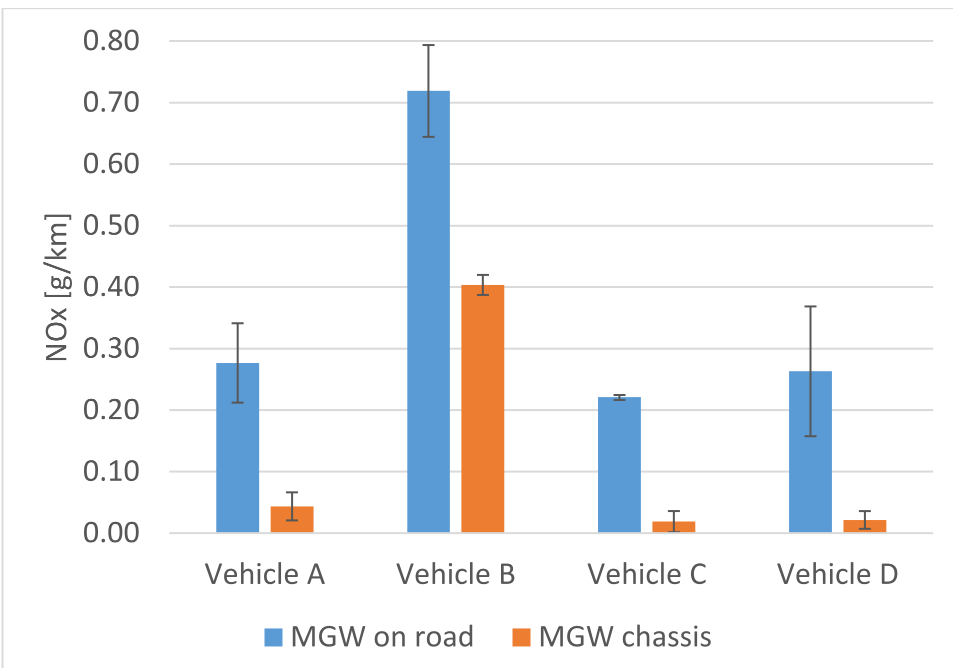

Figure 32 NO_x comparison from Morgantown on-road and chassis test.

Figure 32 shows comparison of average NO_x emissions from Vehicles A to D on on-road tests and chassis tests, along with error bars. Table 4.13 summarizes comparison of NO_x and Fuel economy rates as percent difference.

On-road NO_x emissions are approximately 84 – 92 % high for *Vehicle A, C* and *D* on real world driving when compared with emissions from chassis cycle, whereas *Vehicle B* has 43% more NOx. As this chassis dynamometer cycle does not account for road grade coefficients, the emissions rates are usually high when there is road grade for most part of the route. This can be justified with Relative Positive Acceleration and Characteristic Power calculated for chassis test and on-road tests.

Table 4.13 NO_x & Fuel Economy comparison from Morgantown on-road and chassis test as percent difference.

Routes	**Vehicle A**				**Vehicle B**				**Vehicle C**				**Vehicle D**			
	NO_x		FE		NO_x		FE		NO_x		FE		NO_x		FE	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
MGW On-road	0.27	0.06	23.0	1.59	0.71	0.07	23.8	0.43	0.22	0.00	25.8	0.73	0.26	0.10	23.9	1.02
MGW Chassis	0.04	0.02	31.0	0.67	0.40	0.01	32.6	0.02	0.01	0.01	32.4	0.07	0.02	0.01	31.5	0.70
Diff [%]	84.3		34.6		43.8		36.8		91.5		25.7		91.8		31.8	

Characteristic power (P_{ch}) is derived taking kinematic power, road grade changes and represents mechanical energy. Characteristic power for chassis cycle is low as the elevation is constant throughout the test, making potential energy term to zero. The major difference in characteristic power of on-road test and chassis test is potential energy which also has role in higher NO_x emission rates as well as fuel consumption. From Table 4.13, we observe fuel economy in chassis dynamometer tests are ~ 25 to 36 % higher than on-road tests, which implies lower CO_2 emissions also.

4.3.2 Bruceton on-road route comparison with US06 and HWFET

This part of section covers NO_x emission and Fuel Economy rates comparison between On-road Bruceton route with US06 and HWFET cycles of chassis dynamometer tests. Bruceton route has RPA of about 0.37 m/s^2 and characteristic power of about 4 m^2/s^3 which are similar to of US06, while Bruceton has an average speed of about 87 km/h which is close to HWFET cycle. So, emissions from Bruceton route are compared with US06 and HWFET cycles.

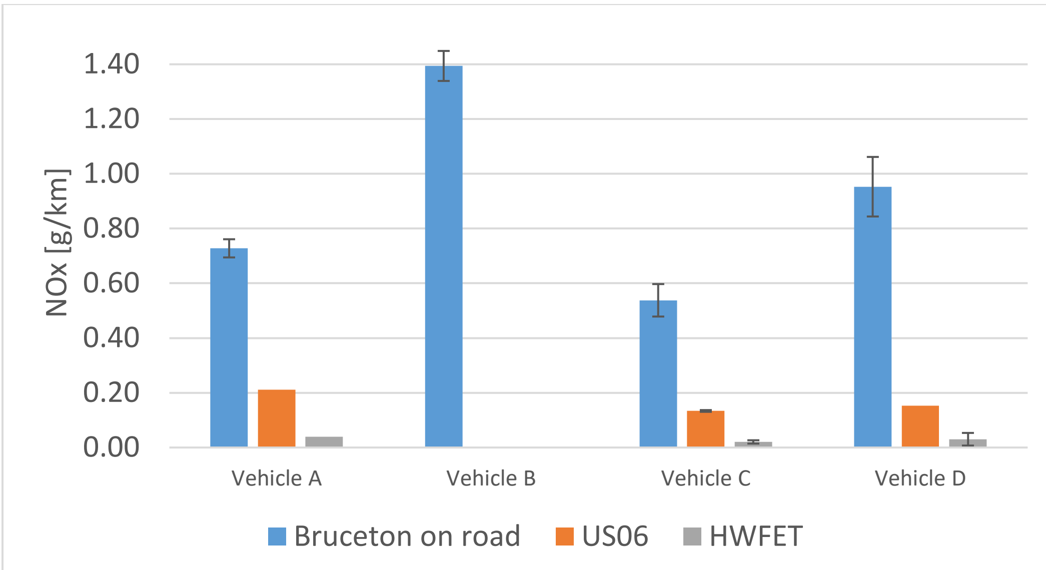

Figure 33 NO_x comparison between on-road Bruceton route & US06, HWFET.

Figure 33 shows comparison of NO_x emissions rates between On-road Bruceton routes with HWFET and US06 chassis cycles. Error bars are plot with standard deviation calculated from tests of minimum two repetitions. *Vehicle B* is not tested on US06 and HWFET chassis cycles so it's represented in the figure. Table 4.14 summarizes the average NO_x emission and Fuel Economy rates along with percentage differences.

Bruceton has an average RPA of about 0.30 m/s^2, whereas US06 and HWFET has 0.52 and 0.18 m/s^2 respectively. NO_x emissions from Bruceton route are high when compared to aggressive cycles like US06 and highway cycle HWFET. This could be because both US06 and HWFET cycles are for 10 min and 13 min each whereas Bruceton route is 50 min approximately. But when emissions are compared on distance specific, duration of test cannot be a reason until and unless there is passive regeneration during the event. More NO_x emission rates in Bruceton is only due to high road grades even though it consists of highway driving for more than 80% of total test. Vehicles A, C & D exhibited 70 – 80% low NO_x emissions in US06 and less than 95% in HWFET cycle compared to Bruceton route emissions.

Table 4.14 NOx comparison between on-road Bruceton route & US06, HWFET.

Routes	**Vehicle A**				**Vehicle B**				**Vehicle C**				**Vehicle D**			
	NO_x		FE		NO_x		FE		NO_x		FE		NO_x		FE	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Bruceton On-road	0.72	0.03	24.6	0.50	1.39	0.05	25.1	0.60	0.53	0.05	25.1	0.13	0.95	0.10	23.2	0.38
US06	0.21	-	28.2	-	-	-	-	-	0.13	0.0	28.4	0.06	0.15	-	28.47	-
HWFET	0.03	-	58.7	-	-	-	-	-	0.02	0.0	45.4	0.33	0.03	0.02	43.2	0.57
Bruceton Vs US06	71.0		14.82		-		-		75.15		13.19		83.96		22.26	
Bruceton Vs HWFET	94.53		138.4		-		-		96.19		81.07		96.82		85.82	

Fuel economy which is also a function of Relative Positive Acceleration of the test, Bruceton route has more fuel consumed though US06 has higher RPA than Bruceton. This could be because of quick accelerations that reduce the fuel economy by 30% on highway and higher elevations. *Vehicles A, C & D* exhibited 13 – 20% higher fuel economy in US06 and about 80% high in HWFET cycle when compared with Bruceton On-road route. *Vehicle A* shows 58.7 mpg in HWFET test which is 138% higher fuel economy than Bruceton route. But the data reported in this report is a Double HWFET cycle which means HWFET cycles are run twice back to back.

4.4 NO_x emissions and temperatures during DPF regen events

Regeneration of DPF is performed in all vehicles regularly to clean the filter of soot that has been traped. All the vehicles used in this study had regeneration event for atleast one time either on road or on chassis. This section describes more about NO_x emissions and exhaust temperatures during a regenration event.

Figure 34 shows continuous plot of NO_x emissions and temperatures of two events, one with regeneration event while the other is a regular event. These events are measured from '*Vehicle B*' while testing in Morgantown route. Regulated NO_x emissions increased substantially during regenerations.

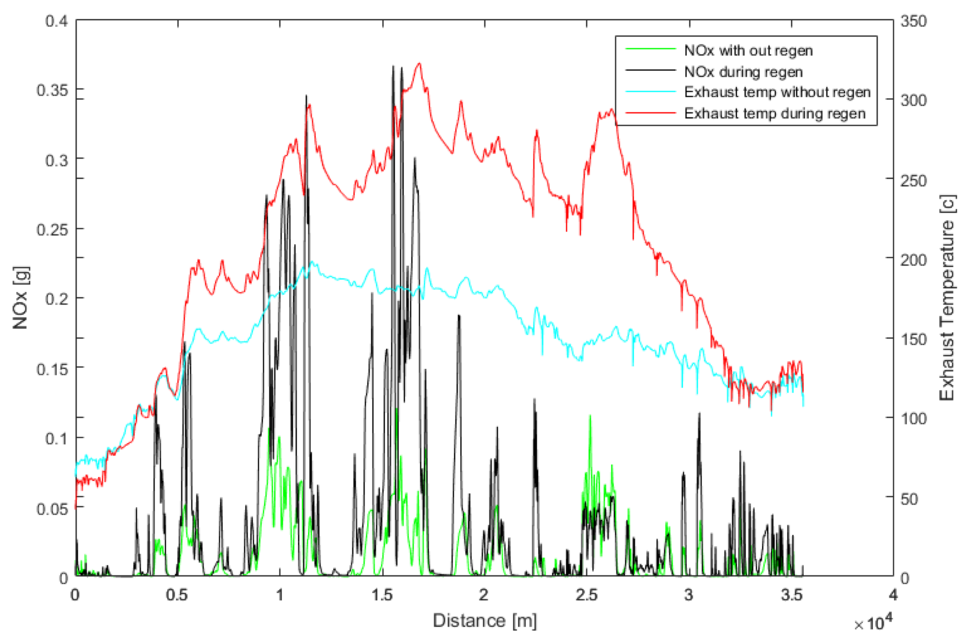

Figure 34 NO_x and Exhaust temperature during a regen and non-regen event over Morgantown route for Vehicle B

Necessity for regeneration arises when there is high pressure difference across the DPF, which also indicates amount of soot accumulation. The duration of regeneration is a function of driving pattern, they need enough temperature to initiate regeneration event. The interval for DPF regeneration event is also based on accumulated mileage on the vehicle.

Table 4.15 Distance based DPF regeneration frequencies & Max. Temp, Avg. NO_x during regen

Vehicles	Regen event	Odometer [km]	Distance b/w events	Duration [min]	Max. Temp [°C]	NO_x [g/km]
Vehicle A	NEDC	3254	-	8	298	0.4125
Vehicle B	Morgantown On-road	21626	384	20	322	1.6407
	Bruceton On-road	22010	-	30	366	1.82
Vehicle C	US06	29611	248	8	323	0.5795
	FTP-75	29859	-	15	280	0.1615
Vehicle D	Morgantown On-road	43236	486	25	354	1.1503
	Bruceton On-road	43722	977	25	367	1.5708
	Morgantown chassis	44699	664	20	345	0.3475
	Morgantown On-road	45363	-	20	328	1.1955

Table 4.15 shows number of regeneration events and the test being performed when regeneration is noticed along with odometer readings before the start of test. This tables provides observed maximum temperature and distance specific NO_x during the events. The distance two consecutive regeneration events is measured as difference between two odometer readings before commencement of the test, so these values are just approximations.

All the vehicles exhibited similar difference in exhaust temperature and NO_x emission patterns while comparing events with regeneration events to a test with no regeneration event. Exhaust temperatures reached as high as 350°C during regeneration, while the distance specific NO_x emissions were 1.6 g/km. As the emissions during regeneration events are unregulated, the frequency of regeneration events depends on strategy that manufacturers employ for NO_x and PM emissions.

Vehicle A had only one regeneration event and the total duration was observed during last 8 minutes of the test after which steady state test is run to clear any of the soot that is still present in the DPF. Even vehicle C has one short duration regeneration event as the test itself is for 10 minutes, so did not contribute much for total NO_x. Vehicle D has more number of regeneration but the distance based frequency are in the range of 500 – 1000 km based on driving patterns, while other vehicles seem to regenerate for every 250 – 400 km. Second regeneration of vehicle D is observed after 977 km which approximately includes 750 km of continuous highway driving with just three stops in between, while all other events does not include highway driving for more than 200 km between each regeneration. This supports the statement that regeneration of DPF depends on on-road conditions and driving pattern.

5 Conclusion

The research presented herein had successfully conducted in-use emission testing of four light-duty diesel vehicles in real world driving situation, with an objective of comparing their corresponding off-cycle emission rates to that of a type approval chassis dynamometer testing, while also assessing their conformity to those values. The chassis dyno testing included a variety of standard test cycles, each representative of certain type of chosen driving condition in some form or the other. Also, the chosen vehicles were operated on pre-defined routes exhibiting four different driving characteristics in these demographics, namely – urban, rural, highway and road grade. The criteria pollutants were analyzed from the tailpipe emissions measurement, per the guidelines outlined in CFR Title 40 Part 1065. The measured data was analyzed using a computer programming code written in MATLAB, and the following conclusions were drawn based on the results stated in section 4.

In summary, real world NOx emissions for all the vehicles under study, were found to exceed the US EPA Tier 2 Bin 5 standard in some way or the other as detailed below. *Vehicle B* NOx values were 1.2 times more than the combined average of the rest of the fleet, under testing. While the on-road PEMS measurement yielded an average distance specific NOx value of 0.87g/km, the FTP-75 based chassis dyno test measured 0.25 g/km. Focusing specifically on the off-cycle operation as an area of prime interest for this thesis, the on-road real world testing indicates that, irrespective of vehicle conditions, all of them emitted about 4 to 35 times higher NOx emissions, when compared with a FTP-75 drive cycle standard limit of 0.04 g/km. Furthermore, when the vehicles were tested on a chassis dyno platform with FTP-75 cycle, similar elevated levels of about 1 to 4 times higher values were found with NOx measurement.

It is interesting to note that, the highest fuel economy among the test candidates was observed in highway route (3% increase) as compared to other urban as well as rural routes. Similarly, on the chassis dyno platform, the highest fuel economy was recorded at 49 mpg with HWFET test cycle, which is a clear representation of a vehicle operating on a highway type driving profile. This figure is 55% significantly higher than the other test cycles, so chosen.

CO emissions inferred from warm engine-start test, are significantly lower as compared to the same values inferred from a cold engine-start test. On road PEMS testing showed 48% lower emission values for this case, while the chassis dyno tests performed over a FTP-75 cycle showed 72% lower CO emissions on a warm engine start test. Finally, with respect to CO_2 emission rates, *Vehicle C* was the least emitter (260 g/km) amongst all the vehicles when measured using a PEMS on road. However, chassis dyno testing proved that *Vehicle B* was the least emitter (188 g/km) of CO_2 with 4.6% lower emission rate among all the vehicles in the fleet.

In general, it can be concluded with substantial evidence that real world scenario exhibits on an average at least two times higher emission rates when compared to the type approval testing performed with representative drive cycle profiles. Although, the standard emissions certification tests, namely FTP-75, NEDC, HWFET have been carefully designed to accommodate the critical parameters that a vehicle experiences while subjected to diverse driving patterns during actual on-road operation, these short timed test procedures carried out on a controlled laboratory environment are not always reliable to provide a realistic evaluation of the vehicle/engine performance. It could be inferred from the present study that, it is always an underestimation of the actual vehicle performance, yielding significantly lower emission concentration values. It is therefore critical to understand and study the emissions trends of light duty engines during off-cycle operations and propose guidelines on improvement for policy makers, which would otherwise not be distinctly recognizable during a chassis dyno base certification test method.

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